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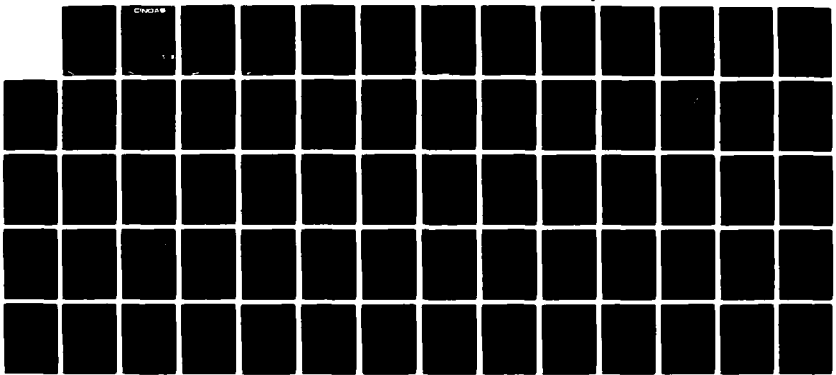
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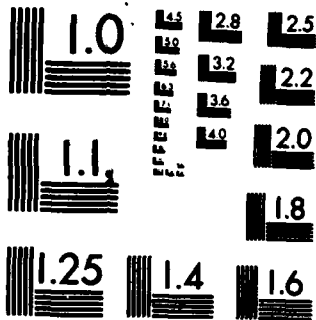
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## ELECTRICAL RESISTIVITY OF VANADIUM AND ZIRCONIUM

By

P. D. Desai, H. M. James, and C. Y. Ho

CINDAS Report 63

December 1982

Prepared for

OFFICE OF STANDARD REFERENCE DATA  
National Bureau of Standards  
U.S. Department of Commerce  
Washington, D.C. 20234

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. <i>ADA 129 176</i>	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) <b>ELECTRICAL RESISTIVITY OF VANADIUM AND ZIRCONIUM</b>		5. TYPE OF REPORT & PERIOD COVERED <b>State-of-the-Art Report</b>
		6. PERFORMING ORG. REPORT NUMBER <b>CINDAS Report 63</b>
7. AUTHOR(s) <b>P. D. Desai, H. M. James, and C. Y. Ho</b>		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS <b>Thermophysical and Electronic Properties Information Analysis Center, CINDAS/Purdue Univ., 2595 Yeager Rd., W. Lafayette, IN 47906</b>		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS <b>Defense Technical Information Center, Defense Logistics Agency, Attn: DTIC-AI, Cameron Station, Alexandria, VA 22314</b>		12. REPORT DATE <b>December 1982</b>
		13. NUMBER OF PAGES <b>66</b>
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) <b>Unclassified</b>
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE <b>N/A</b>
16. DISTRIBUTION STATEMENT (of this Report)  <b>Distribution unlimited.</b>		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES <b>CINDAS/TEPIAC Publication; (DTIC Source Code 413571); Microfiche copies available from DTIC</b>		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) <b>*Electrical Restivity--*Vanadium--*Zirconium--elements--metals</b>		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) <p>→ This work compiles, reviews, and discusses the available data and information on the electrical resistivity of vanadium and zirconium and presents the recommended values resulting from critical evaluation, correlation, analysis, and synthesis of the available data and information. The recommended values presented are uncorrected and also corrected for the thermal expansion of the material and cover the temperature range from 1 K to above the melting point into the molten state. The estimated uncertainties in most of the recommended values are about +2% to +5%. ←</p>		

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## PREFACE

This technical report was prepared by the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, West Lafayette, Indiana, under the auspices of the Office of Standard Reference Data of the National Bureau of Standards (NBS), Department of Commerce, Washington, D.C.

This report represents the most exhaustive compilation and critical evaluation of the recorded world knowledge on the electrical resistivity of vanadium and zirconium, and is one of a series of technical reports on the electrical resistivity of selected elements. The literature search and data compilation have been done in a most extensive and detailed manner, making it possible for all users of the subject to have access to the original data without having to duplicate the laborious and costly process of literature search and data extraction. Also, for the active researchers in the field, a detailed discussion is presented for each material, reviewing the available data and information, giving details of data analysis and synthesis, and discussing the considerations involved in arriving at the final recommended values.

It is hoped that this work will prove useful not only to the engineers and scientists in the field but also to other engineering research and development programs and for industrial applications, as it provides a wealth of knowledge heretofore unknown or inaccessible to many. In particular, it is thought that the critical evaluation, analysis and synthesis, and reference data generation constitute a unique aspect of this work.

Although this report is primarily the result of financial support and interest of the NBS Office of Standard Reference Data, the extensive documentary activity essential to this work was supported by the Defense Logistics Agency of the Department of Defense. Thanks are due Dr. H. J. White, Jr., of the NBS Office of Standard Reference Data for his guidance, cooperation, and sympathetic understanding during the course of this work.

## ABSTRACT

This work compiles, reviews, and discusses the available data and information on the electrical resistivity of vanadium and zirconium and presents the recommended values resulting from critical evaluation, correlation, analysis, and synthesis of the available data and information. The recommended values presented are uncorrected and also corrected for the thermal expansion of the material and cover the temperature range from 1 K to above the melting point into the molten state. The estimated uncertainties in most of the recommended values are about  $\pm 2\%$  to  $\pm 5\%$ .

**Key Words:** vanadium; zirconium; conductivity; critical evaluation; data analysis; data compilation; data synthesis; electrical conductivity; electrical resistivity; elements; metals; recommended values; resistivity.



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\*Figures include the recommended values.

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## NOMENCLATURE

A	Constant in eqs (3b) and (8)
c	Impurity concentration
C	Constant in eq (3a)
e	Base of natural logarithm
h	Planck constant divided by $2\pi$
k	Boltzmann constant
L	Length of specimen at T
$L_0$	Length of specimen at $T_0$
AL	$AL = L - L_0$
M	Atomic weight
RER	Residual resistivity ratio
T	Temperature
$T_0$	Reference temperature
x	$x = h\nu/kT$
a	Constant in eqs (7) and (8)
A	Deviation from the Matthiessen's rule
$\theta_D$	Debye temperature
$\theta_R$	Characteristic temperature for intrinsic electrical resistivity
$\rho$	Electrical resistivity
$\rho_0$	Residual electrical resistivity
$\rho_e$	Electrical resistivity due to electron-electron scattering
$\rho_i$	Intrinsic electrical resistivity
$\omega$	Phonon angular frequency

## 1. INTRODUCTION

The principal objective of this project was to exhaustively compile, critically evaluate, analyze, and synthesize all the available data and information on the electrical resistivity of a large number of selected elements and to generate recommended values over a full range of temperature from 1 K to the melting point and beyond. The results on the electrical resistivity of vanadium and zirconium are presented in this work, which is one in a series of similar works on the electrical resistivity of selected elements, some published [1-3]<sup>1</sup>. The comprehensive study of the electrical resistivity of the elements at the Center for Information and Numerical Data Analysis and Synthesis (CINDAS) has been a continuation of a similar extensive work on the thermal conductivity of the elements [4].

The general background information on this work is given in Section 2, which includes a brief introduction to the theory of the electrical resistivity of metals and a detailed explanation of the specifics and conventions used in the presentation of the data and information.

The experimental data and information and the recommended values for the electrical resistivity of the two elements are presented in Section 3. In the discussion of the electrical resistivity of each element, individual pieces of available data and information are reviewed, details of data analysis and synthesis are given, the considerations involved in arriving at the final assessment and recommendation are discussed, the recommended values and the experimental data are compared, and the uncertainties in the recommended values are stated. The recommended values uncorrected and corrected for the thermal expansion of the material are both presented in this section. The values cover the temperature range from 1 K to above the melting point.

The last three sections are for acknowledgments, appendices, and references. There are two appendices given. The first appendix presents a logical organization of the methods for the measurement of electrical resistivity. The methods are designated with respective code letters and the same code letters are used in the 'Method Used' column of the Table of Measurement Information

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<sup>1</sup>Numbers in brackets indicate literature references listed in Section 6.

for indicating the experimental methods used by the various authors. The second appendix presents conversion factors for the units of electrical resistivity, which may be used to convert easily the electrical resistivity values in the SI units given in this work to values in any of the several other units listed.

## 2. GENERAL BACKGROUND

### 2.1. Theoretical Background

It was found experimentally by Matthiessen [5,6] that the increase in the electrical resistivity of a metal due to the presence of a small amount of another metal in solid solution is independent of the temperature. According to this Matthiessen's rule, the total electrical resistivity of an impure metal may therefore be separated into two additive contributions and written in the form

$$\rho(c,T) = \rho_0(c) + \rho_i(T) \quad (1)$$

where  $\rho_0$  is the residual resistivity caused by the scattering of electrons by impurity atoms and lattice defects and is temperature-independent but dependent on the impurity concentration,  $c$ , and  $\rho_i$  is the temperature-dependent intrinsic resistivity arising from the scattering of electrons by lattice waves or phonons.

In reality, however, deviations from Matthiessen's rule do occur. Thus, in general the electrical resistivity of an impure metal is given by

$$\rho(c,T) = \rho_0(c) + \rho_i(T) + \Delta(c,T), \quad (2)$$

where  $\Delta$  is the deviation from the Matthiessen's rule.

The intrinsic electrical resistivity which is due to scattering of electrons by phonons may be approximated by the Bloch-Grüneisen formula [7,8]:

$$\rho_i = \frac{C}{M\theta_R} \left( \frac{T}{\theta_R} \right)^5 \int_0^{\theta_R/T} \frac{x^5 e^{-x}}{(e^x - 1)^2} dx \quad (3a)$$

$$= A \left( \frac{T}{\theta_R} \right)^5 \int_0^{\theta_R/T} \frac{x^5 e^{-x}}{(e^x - 1)^2} dx, \quad (3b)$$

where  $C$  is a constant characteristic of the metal and proportional to the square of the electron-phonon interaction constant,  $M$  is the atomic weight,  $\theta_R$  is a characteristic temperature of the metal which characterizes its intrinsic electrical resistivity in the same way as the Debye temperature,  $\theta_D$ , characterizes its lattice specific heat, and  $A \equiv C/M\theta_R$ . The dimensionless variable of integration  $x = \hbar\omega/kT$ , where  $\hbar$  is the Planck constant divided by  $2\pi$ ,  $\omega$  is the

phonon angular frequency, and  $k$  is the Boltzmann constant. The derivation of eq (3) is based on the simplifying assumptions that the Fermi surface is spherical, that the conduction electrons can be treated as free in the first approximation, that the spectrum of lattice vibrations is that of the Debye model, that the phonon distribution is essentially undisturbed by the scattering processes, and that electron-phonon Umklapp processes can be ignored. Consequently, it is perhaps most reasonable to expect the Bloch-Grüneisen formula to agree with experiment in the case of monovalent metals. Nevertheless, the intrinsic resistivity of many metals can be well represented by eq (3) over a wide temperature range by a suitable choice of  $\theta_R$  and  $C$ , though no single values of  $\theta_R$  can fit the data at all temperatures.

At low temperatures ( $T \leq \theta_R/20$ ), eq (3a) reduces to

$$\rho_i = \frac{124.4C}{M\theta_R} \left( \frac{T}{\theta_R} \right)^5, \quad (4)$$

while at high temperatures ( $T > \theta_R$ ), to a good approximation, it reduces to

$$\rho_i \approx \frac{C}{4M\theta_R} \left( \frac{T}{\theta_R} \right). \quad (5)$$

Thus it agrees with the experimental facts that at very low temperatures the intrinsic or ideal electrical resistivity (after subtracting  $\rho_0$  from  $\rho$ ) of most metallic elements is proportional to  $T^5$  which is attributed to electron-phonon intraband scattering, and at high temperatures the resistivity of most metals increases approximately linearly with temperature.

In separating the electrical resistivity into its components, the temperature dependent part sometimes includes the electrical resistivity due to electron-electron scattering,  $\rho_e$ ; indeed, this is thought to be the dominant temperature-dependent term in transition metals at low temperatures. That is,

$$\rho = \rho_0 + \rho_e + \rho_i(T). \quad (6)$$

As in the case of the scattering of electrons by phonons, electron-electron collisions are of two types: normal processes in which the total wave vector is conserved, and Umklapp processes in which the total wave vectors before and after the collision differ by a reciprocal lattice vector. On the other hand, unlike electron-phonon Umklapp processes which are frozen out at



low temperatures if the Fermi surface is everywhere clear of the zone boundary, electron-electron Umklapp processes are not frozen out at low temperatures. Normal processes, involving the collision between two s-band conduction electrons, do not contribute directly to the electrical resistivity because they do not change the total momentum and thus have no effect on the current. Normal processes involving the scattering of an s-band conduction electron by a non-conducting d-band electron do contribute to the electrical resistivity, and are thought to be the dominant temperature-dependent resistive processes in transition elements and their alloys at very low temperatures, since their resistivities show the  $T^2$  temperature dependence expected for electron-electron scattering rather than the  $T^5$  temperature dependence expected for the intrinsic resistivity. This temperature dependence of the electrical resistivity due to electron-electron scattering:

$$\rho_0 = \alpha T^2 \quad (7)$$

comes about through the double application of the exclusion principle in the scattering processes; it applies to both the initial states and final states. In eq (7),  $\alpha$  is a constant.

Umklapp processes between two conduction electrons do contribute to the electrical resistivity. Because these processes involve a reciprocal lattice vector, the wave functions of the electrons involved cannot be regarded as simple plane waves, but must be treated as true Bloch functions having the periodicity of the lattice. The results of this are to introduce into the expression for the resistivity the square of an interference factor. Apparently this factor is quite small, as the low temperature electrical resistivity of most ordinary metals does not show the  $T^2$  temperature dependence expected for such a resistive mechanism.

Substituting eqs (7) and (3b) into eq (6) yields

$$\rho = \rho_0 + \alpha T^2 + A \left( \frac{T}{\theta_R} \right)^5 \int_0^{\theta_R/T} \frac{x^5 e^x dx}{(e^x - 1)^2} \quad (8)$$

Equation (8) has been used frequently in analyzing the experimental data and in generating the recommended values for the electrical resistivity at low temperatures.

## 2.2. Presentation of Data and Information

In each of the subsections in Section 3, electrical resistivity data and information for each element are presented in the following order:

- (1) A discussion text.
- (2) A table of recommended values.
- (3) A figure presenting experimental data as a function of temperature in a log-log scale.
- (4) A figure presenting recommended values and selected experimental data (on which the recommendations were based) as a function of temperature in a log-log scale.
- (5) A figure presenting recommended values and selected experimental data (on which the recommendations were based) as a function of temperature in a linear scale.
- (6) A table giving measurement information on the experimental data presented in the figures, and
- (7) A table of experimental data for all the data sets listed in item 6 above.

In the discussion text on the electrical resistivity of each element, individual pieces of available data and information are reviewed, details of data analysis and synthesis are given, the considerations involved in arriving at the final assessment and recommendation are discussed, the recommended values and the experimental data are compared, and the uncertainties of the recommended values are stated.

The recommended values are for well-annealed high-purity specimens of the respective elements; however, those values for low temperatures are applicable only to the particular specimens having residual electrical resistivities as given at 1 K in the tables.

The recommended values uncorrected and corrected for the thermal expansion of the element are both given in the table. The uncorrected and corrected values are related by the following equation:

$$\rho_{\text{corrected}}(T) = \left[ 1 + \frac{\Delta L(T)}{L_0} \right] \rho_{\text{uncorrected}}(T). \quad (9)$$

where  $\Delta L = L - L_0$  and  $L$  and  $L_0$  are the lengths of the specimen at any temperature  $T$  and at a reference temperature  $T_0$ , respectively. The thermal expansion correction amounts roughly to about  $-0.2\%$  at low temperatures, zero at room temperature, about  $0.3\%$  near 500 K, and about  $1.5\%$  to  $2.5\%$  near the melting point of the element.

The recommended values in some cases are given with more significant figures than warranted, which is merely for tabular smoothness or for the convenience of internal comparison. Hence, the number of significant figures given in the table has no bearing on the degree of accuracy or uncertainty in the values; the uncertainty in the values is always explicitly stated.

In the figures, a data set consisting of a single data point is denoted by a number enclosed by a square, and a curve that connects a set of two or more data points is denoted by a ringed number. These data set numbers correspond to those listed in the accompanying tables providing measurement information and tabulating numerical data for each of the data sets. When several sets of data are too close together to be distinguishable, some of the data sets, though listed and tabulated in the tables, are omitted from the figure for the sake of clarity. The data set numbers of those data sets omitted from the figure are asterisked in both tables providing the measurement information and tabulating the experimental data.

The tables providing the measurement information contain for each set of experimental data the following information: data set number, reference number, author(s), year of publication, experimental method used for the measurement, temperature range covered by the data, name and specimen designation, specimen composition, specification and characterization, and information on measurement conditions, which are contained in the original paper. The experimental methods used for the measurement of the electrical resistivity are indicated in the column headed 'Method Used' in the table by the following code letters:

- A Direct-current potentiometer method
- B Direct-current bridge method
- C Alternating-current potentiometer method
- K Direct heating method
- R Rotating magnetic field method
- T Transient (subsecond) method
- V Voltmeter and ammeter direct reading method
- This symbol means either that the method described by the author is not sufficient for assigning a specific code letter or that the use of a code letter would not convey enough of the information reported in the research document, and therefore the method used is described briefly in the last column of the table.

Details of these and other methods for the measurement of electrical resistivity may be found in the literature references given in Appendix 5.1, which presents a complete scheme for the classification and organization of the methods.

In the tables tabulating the experimental data, all the original data reported in different units have been converted to have the same units: the SI units  $10^{-8} \Omega \text{ m}$ . The recommended values generated are also given in the same units. Conversion factors for the units of electrical resistivity, which may be used to convert the electrical resistivity values in the SI units given in this work to values in other units, are given in Appendix 5.2.

### 3. ELECTRICAL RESISTIVITY DATA AND INFORMATION

#### 3.1. Vanadium

There are 69 sets of experimental data available for the electrical resistivity of undoped vanadium as a function of temperature. The residual resistivity of the purest sample reported in this investigation is  $0.01008 \times 10^{-8} \Omega \text{ m}$ . Information on the specimen characterization and measurement condition for each of the data sets is given in table 2. The data are tabulated in table 3 and shown partially in figure 1.

In the absence of a magnetic field, vanadium is a superconductor below its superconducting transition temperature (5.46 K). The superconducting transition temperature is very sensitive to the magnetic field intensity: the higher the magnetic field intensity, the lower is the superconducting transition temperature. Aleksandrov et al. [19] found that the superconducting transition temperature of vanadium would be lowered to 4.5 K in a magnetic field of  $\sim 0.5$  kOe. Furthermore, their measurements for the nonsuperconducting state of a high purity vanadium specimen at  $\sim 5.4$  K in a magnetic field of  $\sim 2.2$  kOe showed an increase of about 0.45% in the electrical resistivity; thus the influence of the magnetic field on the electrical resistivity of very pure vanadium could be neglected.

The electrical resistivity measurements below room temperature have received considerable attention. This is evident in the extent of the measurements of Pan et al. [13] (data sets 6,7), Courtney [14] (data sets 8-11), Chakal'skii et al. [15] (data set 15), Jung et al. [16-18] (data sets 13-16), Aleksandrov [19] (data sets 17,18), Azhazha et al. [20] (data sets 19,20), Westlake and Alfred [37,38] (data sets 37,38), Amitin et al. [40] (data sets 41,42), Taylor and Smith [45] (data sets 52-55), and White and Woods [48,49] (data set 59). Very recent studies have been made by Gautron et al. [53] (data set 64) on a sample with the highest purity (i.e., lowest  $\rho_0 = 0.01 \times 10^{-8} \Omega \text{ m}$ ) and by Tsai et al. [54] (data sets 65,66) on a sample with  $\rho_0 = 0.0109 \times 10^{-8} \Omega \text{ m}$ .

The temperature dependent part of the electrical resistivity below 21 K was reported to be proportional to  $T^3$  by White and Woods [48,49]. This was confirmed later by results of Chakalskii et al. [15], Jung et al. [16-18], and

by Aleksandrov et al. [19]. The presence of the cubic term is evidently connected with s-d interband scattering. However, studies of Tsai et al. [55] on the sample with  $\rho_0 = 0.0109 \times 10^{-8} \Omega \text{ m}$  found an additional  $T^2$  term which they attributed to electron-electron scattering ( $\rho_e$ ). In order to verify these results, Gautron et al. [53] carried out electrical resistivity measurements on an even purer specimen with  $\rho_0 = 0.01 \times 10^{-8} \Omega \text{ m}$ , and obtained a value of  $(1.6 \pm 0.2) \times 10^{-11} \Omega \text{ cm/K}^2$  for  $\rho_e$  that was compatible with the value of  $(1.3 \pm 0.2) \times 10^{-11} \Omega \text{ cm/K}^2$  obtained by Tsai et al. [54]. Gautron et al. [53] pointed out that the temperature dependent electrical resistivity above 10 K is dominated by electron-phonon interactions. Below 10 K, the electron-electron term makes a significant contribution, and it begins to dominate below 5 K. Failure to detect the  $\rho_e$  term in earlier studies [e.g., 15-18, 48-50] was attributed to the fact that these studies did not involve measurements to low enough temperatures, and also to the fact that below 10 K the electron-electron contribution is of the order of or less than  $\rho_0$ , even for relatively pure specimens.

An anomalous behavior of the electrical resistivity between 180 and 300 K has been observed by Burger and Taylor [46], Suzuki et al. [74], Smirnov and Finkel [67], and by Rostoker and Yamamoto [73]. However, Westlake [38] found that hydrogen absorbed in the specimen affects the resistivity anomalously near 180 K and that hydrogen-free vanadium did not show such anomalous behavior.

Comparison of the electrical resistivity data below room temperature indicates that the electrical resistivity of vanadium deviates from Matthiessen's rule. The deviations are dependent not only on the concentration of impurities, but also on their type. The deviations are larger for the less pure specimens.

With the discussion given above in mind, the recommended values are based on the data of Courtney [14] (data set 11), Jung et al. [16-18] (data sets 13-16), Gautron et al. [54] (data set 64), and of Tsai [55] (data set 65), who all measured specimens with RRR > 1500. Special weight was given to the data of Gautron et al. [54] on a specimen with RRR = 1970 and  $\rho_0 = 0.01 \times 10^{-8} \Omega \text{ m}$ . The deviation of the data from the recommended values for somewhat less pure specimens [13,19,20,37,38,40,45,48,49] are shown in figure 1.

At the highest temperatures there is general agreement on the temperature dependence of the electrical resistivity. There are little good data from 300

to 1200 K. The recommended values in this temperature range are based on the data of Neimark et al. [28] (data set 26) and of Taylor and Groot [55] (data set 67). However, Neimark et al. have indicated rather high maximum error for their measurements, and  $RRR = 400$  is reported by Taylor and Groot [55] for their sample. The recommended values from 1200 to the melting point are based on the data of Gathers et al. [10] (data set 2), Cezairliyan et al. [22-24] (data set 22), and of Peletskii et al. [32] (data set 30) [57] (data set 69). A compromise has been made between their somewhat divergent results. The scatter of the data from other investigations reported in table 2 [12,28-30,33,34,36,43,44,56] is of the order of  $\pm 10\%$ . The recommended values above 2202 K, in the liquid region, are based on the compromise between the only two data sets available, due to Seydel and Fucke [9] (data set 1) and to Gathers et al. [10] (data set 2). At 4000 K the divergent in their values approaches 9%. The data of Gathers et al. [10] indicate a lower melting point than the generally accepted value of 2202 K, presumably because their data were taken under pressure.

The recommended values of the electrical resistivity given in table 1 and shown in figures 2 and 3 along with the experimental data, which were used to generate these values, are for vanadium of 99.99% purity or higher, but those below 100 K are applicable specifically to vanadium having a residual resistivity of  $0.0100 \times 10^{-8} \Omega \text{ m}$ . The table gives both values uncorrected and corrected for thermal expansion, while the figures show only the uncorrected recommended values and mostly uncorrected experimental data. The values for the thermal expansion were taken from ref. [121]. The uncertainty in the recommended values is estimated to be within  $\pm 10\%$  from 7 to 20 K and  $\pm 5\%$  at lower and higher temperatures.

Vanadium is a transition element and its low-temperature electrical resistivity depends on the type as well as on the concentration of impurities. The electrical resistivity of lower-purity vanadium is, therefore, difficult to estimate, especially at low temperatures ( $< 250 \text{ K}$ ). However, judging from the data reported by Jung et al. [16-18], it appears that for specimens having residual resistivities less than  $0.5 \times 10^{-8} \Omega \text{ m}$  only small uncertainties ( $< 0.01 \times 10^{-8} \Omega \text{ m}$  at 20 K, and  $\sim 0.3 \times 10^{-8} \Omega \text{ m}$  at 100 K) are introduced by the application of Matthiessen's rule. The data from refs. [16-18] (data set 13) and from ref. [38] (data set 38) with sample residual resistivity of  $0.52 \times 10^{-8} \Omega \text{ m}$  and  $0.81 \times 10^{-8} \Omega \text{ m}$ , respectively, are also shown in one of the figures for illustration.

Additional information on the electrical resistivity is reported in refs. [58-95]. Data of Hensler et al. [35] (data sets 33,34), Gurp [41] (data sets 43,44), and of Wruk and Wert [51] (data sets 61,62) are for films/foils; readers are directed to refs. [96-115] for additional information/data on films. The data of Courtney [14] (data sets 8-10) are hydrogen-doped vanadium and additional information/data on various doped-vanadium samples are reported in refs. [65,72,102,116-119]. Effects of irradiation are discussed in refs. [71,72,120], of annealing temperature in refs. [66,112,116,120], and of pressure in refs. [73,74,122].

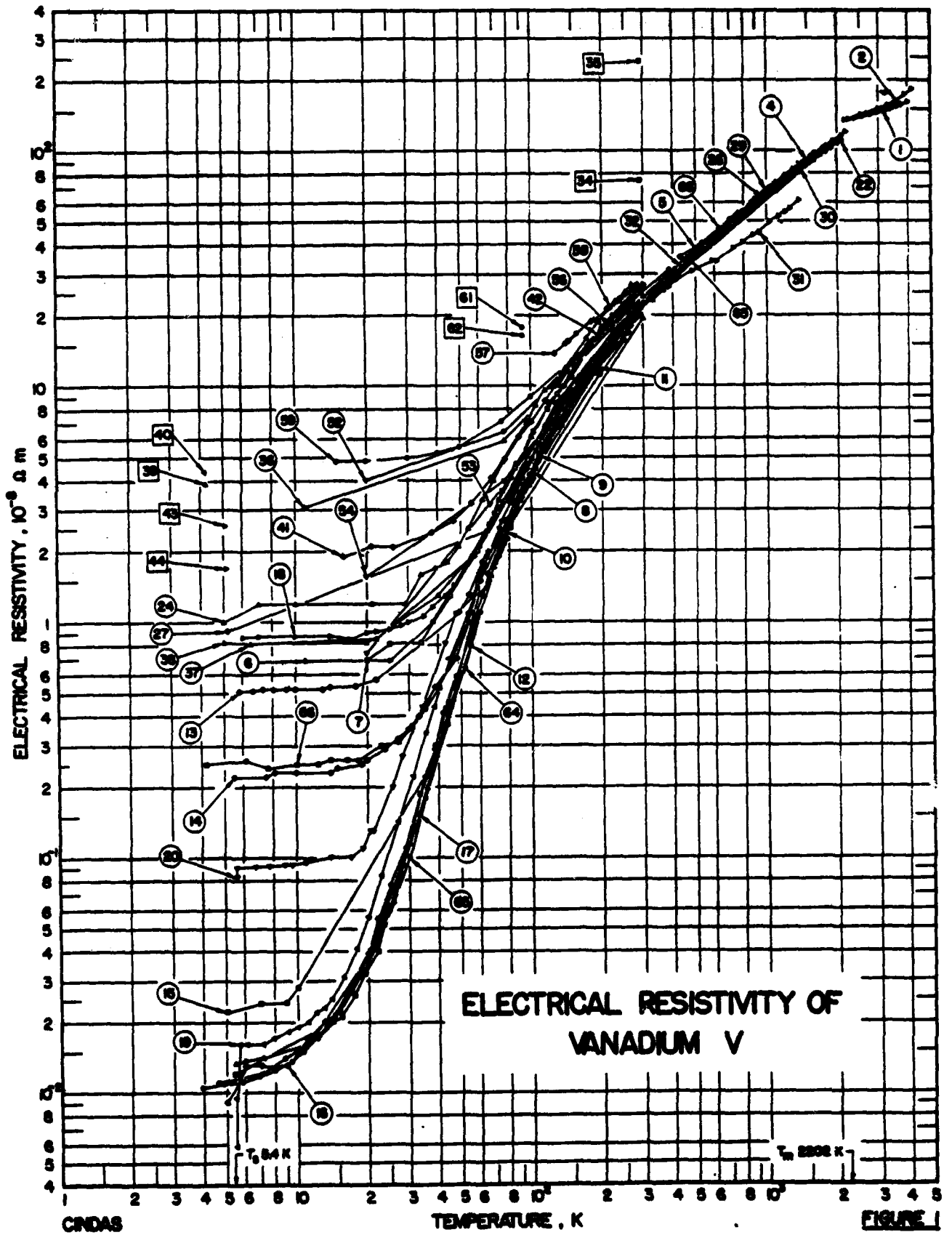


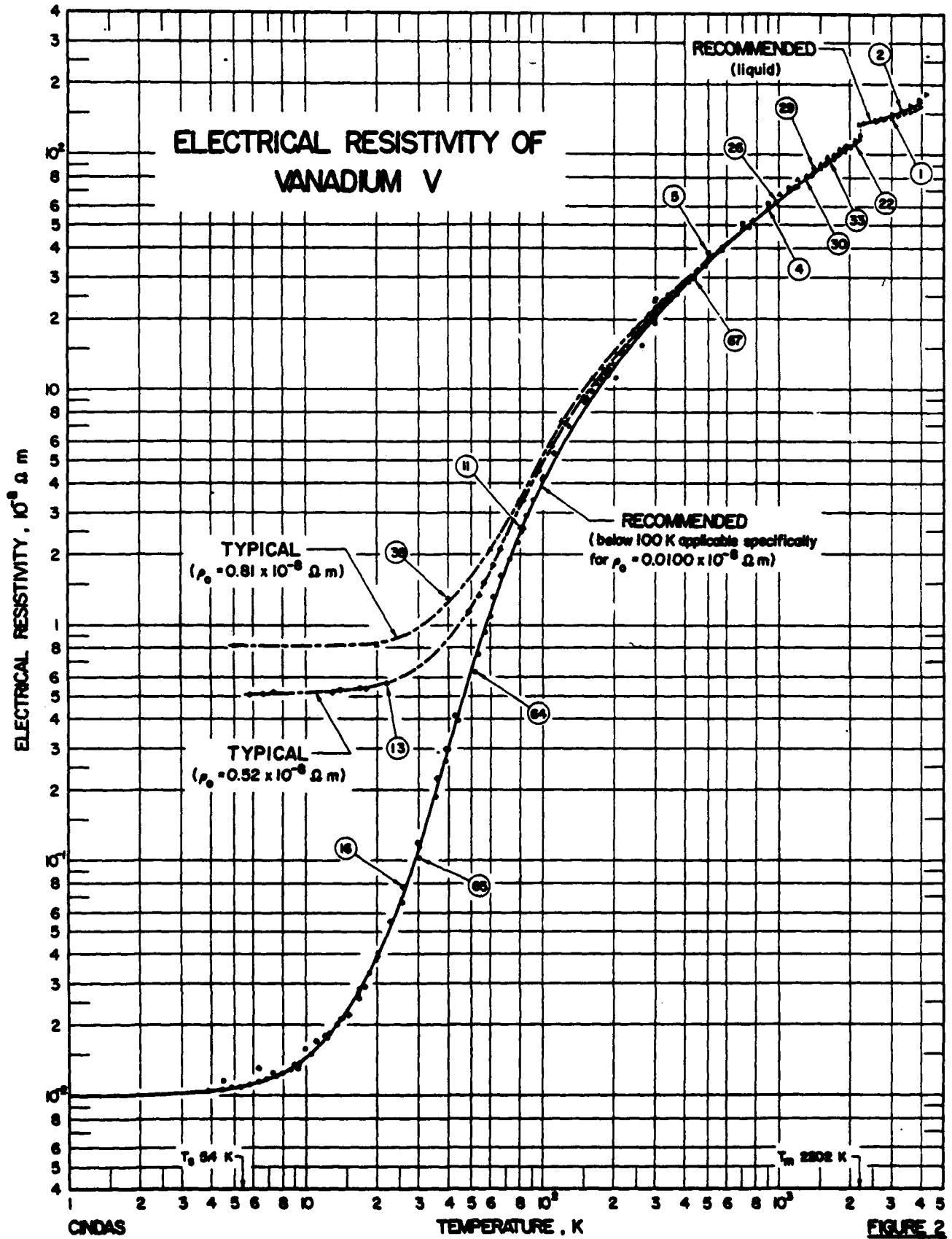
TABLE 1. RECOMMENDED VALUES FOR THE ELECTRICAL RESISTIVITY OF VANADIUM<sup>a</sup>[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

T	$\rho$		T	$\rho$	
	uncorrected	corrected		uncorrected	corrected
1	0.0100 <sup>(b)</sup>	0.0100	700	47.2	47.4
4	0.0105	0.0105	800	53.1	53.4
7	0.0117	0.0117	900	58.7	59.1
10	0.0145	0.0145	1000	64.1	64.6
15	0.0232	0.0232	1100	69.1	69.7
20	0.0391	0.0391	1200	73.8	74.5
25	0.0661	0.0660	1300	78.5	79.4
30	0.112	0.112	1400	83.2	84.2
40	0.304	0.304	1500	87.8	89.0
50	0.649	0.648	1600	92.3	93.7
60	1.114	1.112	1700	96.7	98.3
70	1.706	1.703	1800	100.9	102.7
80	2.413	2.409	1900	104.9	107.0
90	3.196	3.191	2000	108.7	111.0
100	4.01	4.00	2100	112.2	114.8
150	8.22	8.21	2202	115.6(s)	118.5(s)
200	12.43	12.42	2202		135.1(l)
250	16.37	16.36	2400		137.6
273	18.14	18.14	2600		140.4
293	19.68	19.68	2800		143.3
300	20.21	20.21	3000		146.4
350	24.2	24.2	3200		149.7
400	28.0	28.0	3400		153.3
500	34.8	34.9	3600		157.5
600	41.1	41.2	3800		162.0
			4000		166.8

<sup>a</sup>The values are for vanadium of purity 99.99% or higher, but those below 100 K are applicable specifically to vanadium having a residual resistivity of  $0.0100 \times 10^{-8} \Omega \text{ m}$ . The columns headed uncorrected and corrected refer to values uncorrected and corrected for thermal expansion, respectively. Solid line separating tabular values indicates solid to liquid state transformation.

<sup>b</sup>Assuming superconductivity suppressed by magnetic field.





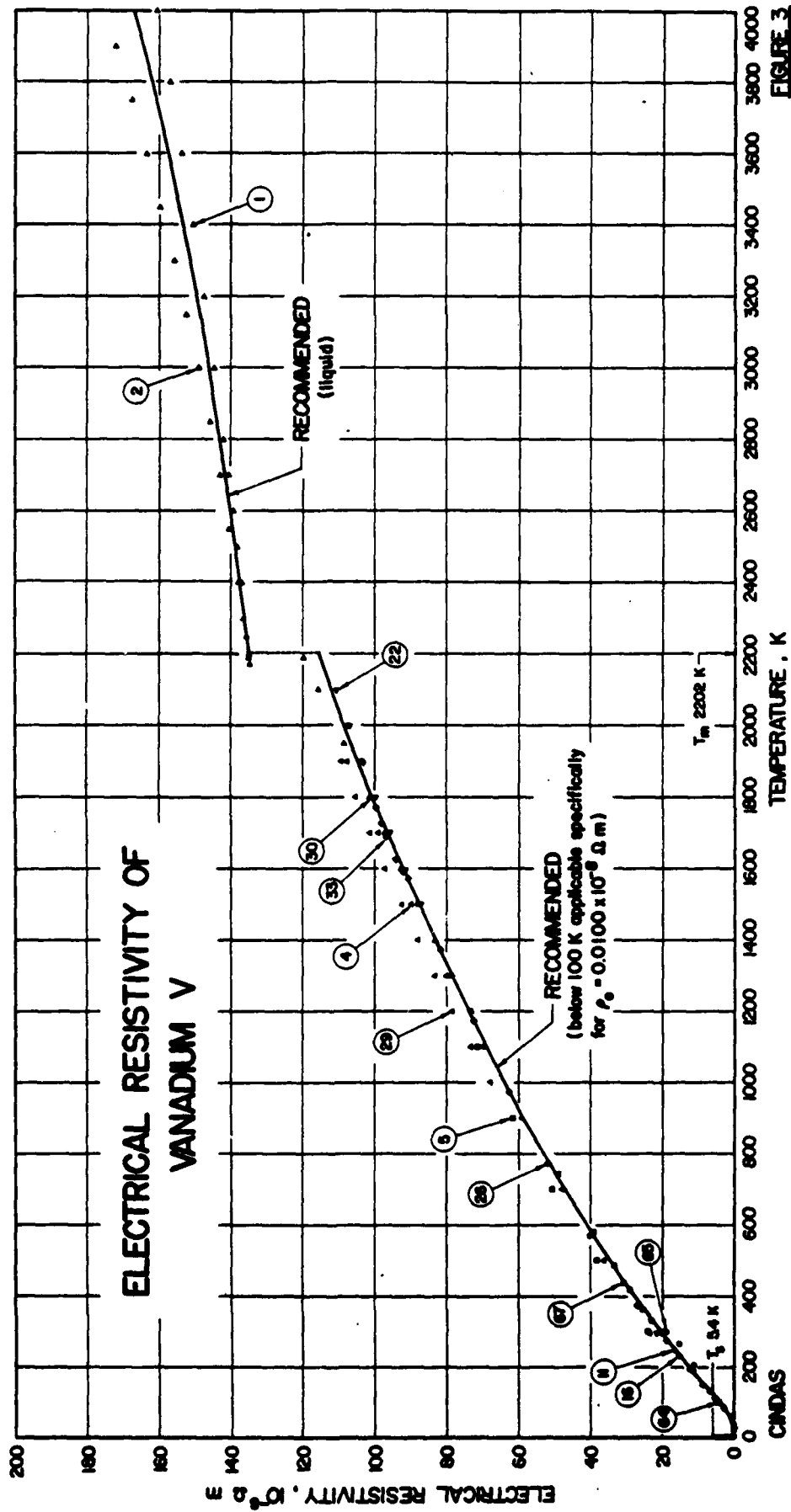


FIGURE 3

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF VANADIUM V

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
1	9	Seydel, U. and Fuchs, W.	1980	T	2173-4000		99.9 V; temperature measurements taken on foil samples, length 4.4 cm, cross sections $5 \times 10^{-4}$ cm <sup>2</sup> ; heated by means of a capacitor discharge with a heating rate of $10^{11}$ K s <sup>-1</sup> ; for the range of T <sub>c</sub> (melting temperature) = 2173 K $\leq$ T $\leq$ 6600 K, $\rho$ ( $\mu\Omega$ cm) = $1.3486 + 1.0219 \times 10^{-4}(T-T_m) + 2.1803 \times 10^{-6}(T-T_m)^2$ ; error in $\rho$ stated as 5-8%.
2	10	Gachera, G.R., Shamer, J.W., Hinson, R.S., and Young, D.A.	1979		1800-4200		Wire sample 1.0 mm diameter, 25 mm long; phase change from solid to liquid occurs at 2190 K; resistivity values measured at 0.3 GPa; for the solid, $\rho_0$ ( $\mu\Omega$ m) = $0.1077 + 5.3699 \times 10^{-4}T - 1.7255 \times 10^{-6}T^2$ , 1800 K $\leq$ T $\leq$ 2190 K; least squares fit of data; smoothed values listed.
3*	11	Vedernikov, M.V., Dremithin, V.G., and Zhmogolov, A.	1978	A	4.2, 293		No details given.
4	12	Felotskii, V.R., Ananovich, E.S., Kostomarov, A.V., Zaretckii, E.B., Sobol, Ya.G., and Shur, B.A.	1977	A	300-1900	V1	99.8 V, 0.01 C, 0.09 Os, 0.02 Si, 0.02 Al, 0.02 Fe; density 6.1 g cm <sup>-3</sup> ; crystal orientation [100]; data not corrected for thermal expansion; error does not exceed $\pm 1.5\%$ from 300 to 1600 K and $\pm 2-5\%$ from 1600 to 2000 K; data extracted from smooth tabulated values.
5	12	Felotskii, V.R., et al.	1977	A	300-2000	V2	99.9 V, 0.06 C, 0.02 Os, 0.01 Si, 0.01 Zr, 0.01 Al; density 6.097 g cm <sup>-3</sup> ; crystal orientation 3° [001]; other specifications are same as above.
6	13	Fan, V.M., Frohrorev, V.G., Shevchenko, A.D., and Dorygopol, V.P.	1977	A	11-300		Single crystal specimens; measurements taken with two directions of current flow <100> and <110>; critical temperature for superconductive transition 5.22 K; $\rho_{300}/\rho_0 = 43$ , temperature coefficient of resistivity at 300 K $4.1 \times 10^{-4}$ K <sup>-1</sup> ; application of magnetic field of 40 kOe did not change the temperature dependence of $\rho$ or shift the position of T <sub>c</sub> ; data extracted from figure reported for measurements in zero magnetic field; values reported at 6 K are $0.5 \times 10^{-8}$ $\Omega$ m and $21.5 \times 10^{-9}$ $\Omega$ m at 300 K.
7	13	Fan, V.M., et al.	1977	A	20-300		Same as above except magnetic field H = 40 kOe.
8	14	Courtney, D.R.	1977	A	95-288	VR330	Electro-transported rods electropolished in a 94-6% methanol-perchloric acid, then subjected up to $10^{-7}$ torr in a vacuum furnace and heated to 1000°C for 1 1/4 hr and at 800°C in H <sub>2</sub> for 2 hr; specimen length 4.3 cm and 0.23 cm diam.; 330 ppm H, 140 ppm O, 10 ppm N, 15 ppm C, and 165 ppm OHH+C; data from figure.
9	14	Courtney, D.R.	1977	A	76-296	VR260	Same as above except 260 ppm H, 60 ppm O, 3 ppm N, 18 ppm C, and 81 ppm OHH+C; specimen length 3.92 cm and 0.244 cm diameter.
10	14	Courtney, D.R.	1977	A	79-283	VR54	Same as above except 54 ppm H, 27 ppm O, 1 ppm N, 11 ppm C, and 39 ppm OHH+C; specimen length 2.9 cm and 0.242 cm diameter.

\*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Mass and Specimen Designation	Composition (weight percent), Specifications and Remarks
11	14	Courtney, D.R.	1977	A	81-295	VN1	Same as above except <1 ppm H and 15 ppm (O+H+C); specimen length 3.65 cm and 0.205 cm diam.; data of Jung [16,17].
12	15	Chahal'akhid, B.K., Akhachev, V.M., Rod'ko, B.A., and Shalyt, S.S.	1976	A	5-155		No details given; specimen same as that reported in data set 17.
13	16	Jung, W.D.	1975	A	6-273	Sample 1	Specimen prepared by Schmidt of the Ames Laboratory using electro-transport technique from the polycrystalline double-electrorefined vanadium supplied by the U.S. Bureau of Mines; total impurities 100 atm ppm consist of 30 atm ppm Cl, 23 atm ppm W, 22 atm ppm Cu, 10 atm ppm Fe, 5 atm ppm Mo, 4 atm ppm Mg, and 3 atm ppm Si (separate source mass-spectrometry and neglecting 1230 atm ppm O+H); $\rho_{11}/\rho_{0,1} = 37.6$ ; $\rho_{11}$ = $19.61 \times 10^{-8} \Omega \cdot m$ ; specimen diameter 0.263 cm diameter and 2.5 cm length; data extracted from figure.
14	16	Jung, W.D.	1975	A	6-265	Sample 2	Same as above except 570 atm ppm (O+H); $\rho_{11}/\rho_{0,1} = 81.5$ and $\rho_{11}$ = $18.72 \times 10^{-8} \Omega \cdot m$ ; specimen diameter 0.260 cm diameter and 3.47 cm length; data extracted from figure.
15	16	Jung, W.D.	1975	A	5-283	Sample 3	Same as above except 55 atm ppm O+H, 100 atm ppm Cr+V, 12 atm ppm W, 13 atm ppm Fe, 14 atm ppm Cl, and 8 atm ppm Mg; no evidence of an impurity gradient; large concentration of Cr+V likely due to surface hydrocarbon contamination not representative of sample; $\rho_{11}/\rho_{0,1} = 785$ and $\rho_{11}$ = $18.69 \times 10^{-8} \Omega \cdot m$ ; specimen diameter 0.205 cm diameter and 3.65 cm length; data extracted from figure.
16	16	Jung, W.D.	1975	A	5-276	Sample 4	Same as above except 28 atm ppm O+H; $\rho_{11}/\rho_{0,1} = 1524$ and $\rho_{11}$ = $18.90 \times 10^{-8} \Omega \cdot m$ ; specimen diameter 0.241 cm diameter and 4.3 cm length; data extracted from figure.
17	19	Aleksandrov, B.H., Semenova, E.B., Petrova, O.I., Cheryi, B.P., and Akhachev, V.M.	1975	A	5-300	Specimen No. 1	Polycrystalline; purest sample they studied is 1.4 mm diameter and 25-60 mm length; $\rho_0 = 0.0129 \times 10^{-8} \Omega \cdot m$ ; data extracted from figure.
18	19	Aleksandrov, B.H., et al.	1975	A	6-67	Specimen No. 4	Similar to above except $\rho_0 = 0.067 \times 10^{-8} \Omega \cdot m$ ; least pure sample which studied; data extracted from figure.
19	20	Akhachev, V.M., Volkenshchkin, B.V., Startsev, V.Ye., Fisbal, V.A., Cheremov, V.I., and Cheryi, B.P.	1976	A	5-270	V4	High purity sample of $\rho_{100}/\rho_0 = 1520$ prepared by complex method includes refining by vacuum electron beam melting and electron transfer; total impurities $< 3 \times 10^{-3}$ %, gas impurities 1%, and <1% hydrogen; superconducting transition temperature $T_c = 5.39$ K; error of the measurement 0.5% for $T < 15$ K and 0.01% for $T > 70$ K; anomaly near 183 K was observed; resistivity contains contribution proportional to fourth power of the temperature; these peculiarities are intensified as the purity of sample increases; data extracted from figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF VAMADIN V (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Mass and Specimen Designation	Composition (weight percent), Specifications and Remarks
20	20	Ashaba, V.M., et al.	1976	A	5-272	V6	Same as above except $D_{212}/D_0 = 220$ and $T_c = 5.52$ K.
21*	21	Alexeevskii, H.E., Mitsin, A.V., and Matveeva, H.M.	1975	→	300		99.9 V; resistance measured using electronic amplifier with x-y recorder.
22	22	Cesariyev, A., Righini, F., and McClure, J.L.	1974	Y	293-2100		99.9 V; polycrystalline; from Materials Research Corp.; 120 ppm C, 20 ppm Fe, 60 ppm Nb, 10 ppm W, 15 ppm O, 15 ppm P, 50 ppm Si, 70 ppm Ti, 10 ppm Ta, 30 ppm V, 15 ppm Zr, other total less than 50 ppm; tube made from rod by electro-erosion, 6.3 mm diameter (outside), 76.26 mm long; density $6.1 \text{ g cm}^{-3}$ ; heat treated by pulse heating -30 pulses to 1900 K; 0.5% estimated total error in measurement; experimental vacuum $\sim 10^{-8}$ torr.
23*	23	Beckett, C.W.	1974				
23*	25	Humpal, K. and Ohtsuka, T.	1974	A	300		99.95 V from Material Research Corp. (V-P grade); method is electron beam furnace at pressures below $10^{-5}$ torr to outgas sample; $T_c = 5.20$ K; $D_{212}/D_0 = 20.0$
24	26	Prehal, A.F., Buseckhin, V.A., and Polkubskaya, N.V.	1974	A	5-267		No details are given; data extracted from figure.
25*	27	Lung, E. and Broecker, J.	1975	A	77,293	V811	Single crystals of [491] orientation; <10 ppm $O_2$ , <5 ppm of other interstitials and substitutionals; prepared by electron beam melting under UHV conditions, annealed at 1373 K; $D_{212}/D_0 = 8.59$ ; ideal resistivity ratio 0.116; results of oxygen doping of V crystals indicated a linear increase of resistivity with increasing $O_2$ content.
26	28	Reimark, B.E., Belyubova, P.E., Bredikhin, B.H., Vorontsov, L.K., Korytina, S.P., and Mikhailov, A.H.	1973	→	293-1773	V8L2	99.82 V, 0.05 Al, 0.02 Ni, 0.01 Fe, 0.026 C, 0.003 Si, 0.07 O; specimen of V fused by electron beam in vacuum from pressed powder; annealed at 900°C in vacuum of $10^{-6}$ mm Hg and at 1540°C of $10^{-4}$ mm Hg; resistivity in the range 20-1100°C measured by Jaeger-Dieselhorst method and in the range 900-1400°C by Bode method; agreement between these two measurements is $\pm 15\%$ within minimum error of measurements; resistivity value at 293 K increased from $21.3 \times 10^{-8} \Omega \text{ m}$ to $27.3 \times 10^{-8} \Omega \text{ m}$ after heating the specimen to 1100°C; data extracted from smooth tabulated values.
27	29	Chernoplev, H.A., Pomova, G.M., Samuilov, B.N., and Shibov, A.A.	1973		5-1032		Pure V (no purity or source mentioned); sample rod 60 mm long with cross section $0.7 \times 0.7$ mm; values extracted from smooth values from small figure.
28*	30	Arutyunov, A.V., Mikharukho, I.H., and Filippov, L.F.	1972		1000-1900		95.72 V, 0.13 Al, 0.09 Si, 0.05 Fe, 0.04 C, 0.055 O, 0.001 H, and 0.01 W; annealed in vacuum at 1600 K for 2 hr; sample 12 mm diameter and 90 mm length; the data reported here appeared to be same as in data set 25.

\*Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
29	31	Filippov, L.P. and Yurchak, R.P.	1971	A	1000-1900		99.72 V, 0.13 Al, 0.09 Si, 0.05 Fe, 0.005 O, 0.04 C, 0.01 Ni; polycrystalline; solid and hollow rod; 90 mm length and 12 mm diameter; data extracted from smooth tabulated values; error is 2%.
30	32	Pelateckii, V.E., Drenskina, V.P., and Sobol, Ya.G.	1971	A	293-1800		99.94 V, <0.001 Al, <0.001 Ni, <0.001 Fe, <0.046 O, <0.01 H, <0.001 Si; polycrystalline; density $6.099 \text{ g cm}^{-3}$ ; specimen machined from a rod produced by electron beam melting in vacuum; specimen dimensions 10 mm diameter $\times$ 60 mm length; measurements in vacuum of $10^{-4}$ torr; measurements error 1.8-2.0%; data extracted from smooth tabulated values.
31	33	L'vov, S.B., Mal'ko, P.I., and Munchenko, V.F.	1971		341-1381		99.9 V.
32	34	Voronin, L.K., Merkulov, A.B., and Reimark, B.E.	1970	A	283-1548	VEL2	99.82 V, 0.01 Fe, 0.02 Ni, 0.05 Al, 0.003 Si, 0.07 O, 0.001 H, <0.001 N, 0.024 C; electron beam melting of pressed powder; annealed at 1173 K; $1 \times 10^{-4}$ mm Hg for 1 hr before measurements; sample size 150 mm $\times$ 6 mm diameter; measurements made by Jeager-Discalhorst method.
33	34	Voronin, L.K., et al.	1970	A	1591-1727	VEL2	Similar to the above except sample size 70 mm $\times$ 2 mm diameter; measurements made at $2 \times 10^{-4}$ mm Hg by Bode method.
34	35	Rensler, D.H., Ross, A.R., and Falls, E.H.	1970	A	293		Film deposited on sapphire substrate by sputtering from V cathode; substrate held at 673 K during sputtering and for 30 minutes post deposition annealing in vacuum and cooled slowly over several hours; thickness of film 1970 Å; temperature of measurements not reported but assumed to be 293 K.
35	35	Rensler, D.H., et al.	1970	A	293		Film deposited on sapphire substrate by sputtering from V cathode in oxygen $10^{-4}$ torr; thickness of film 1950 Å; other specifications are same as above.
36	36	Buehner, U.	1969		11-1090		Pure V, 0.08 O, 0.046 H, and 0.044 C; fused by electron beam; sample 80 mm long and 5 mm diameter; data extracted from figure.
37	37	Westlake, B.G. and Alfred, L.C.R.	1968	A	6-350		No details are given.
38	38	Westlake, B.G.	1967	A	5-338		Crystals of electrolytic vanadium from U.S. Bureau of Mines; 230 ppm metallic impurities, 20 ppm C, 100 ppm H, 290 ppm O; crystals electron-beam melted into ingot, rolled to 0.64 mm strips, 60 mm long $\times$ 4.2 mm wide cut from sheet, and both rolled surfaces were ground on wet 600-grit SiC paper to produce specimen 0.4 mm thick; specimens were wrapped in Mo foil, vacuum encapsulated in quartz, annealed 4 hr at 1273 K; annealed further in dynamic vacuum $2 \times 10^{-4}$ torr for 30 minutes at 1073 K for dehydrogenation; data extracted from figure.



TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
39	39	Verbeiner, H.R. and Gilchrist, J.G.	1967	R	4.2	V1	Specimen from Isply Kulmann; 0.3% total impurity; 87% cold drawn.
40	39	Verbeiner, H.R. and Gilchrist, J.G.	1967	R	4.2	V2	Same as above except 97% cold drawn.
41	40	Amitin, E.B., Kovalovskaya, Yu.A., and Kovdya, Yu.Z.	1967		16-299	Sample 1	99.63 V; polycrystalline; 13.1 x 3.7 x 0.8 mm plate prepared by cutting with corundum disk under emulsion layer subjected to 10 <sup>5</sup> atm pressure at 293 K to suppress possible porosity; sample annealed in 10 <sup>-6</sup> mm Hg at 1123 K for 5 hr; density 6.2 g cm <sup>-3</sup> ; $\rho_{273}/\rho_0 = 11.5$ ; data obtained from $\rho_T/\rho_{273}$ from figure and $\rho_{273} = 24.1 \times 10^{-9} \Omega \text{ m}$ reported by authors.
42	40	Amitin, E.B., et al.	1967		131-277	Sample 2	Sample supplied by Metal Physics Institute of Academy of Sciences of the USSR; $\rho_{273}/\rho_0 = 15$ ; data obtained from $\rho_T/\rho_{273}$ from figure and $\rho_{273} = 23.6 \times 10^{-9} \Omega \text{ m}$ from Mathieson's rule.
43	41	Van Gorp, G.J.	1967	R	5.1		99.9 V, 0.05 Si, 0.03 Fe, 0.04 Ti, 0.1 O, 0.06 H; specimen from A. C. Machly Ltd.; in the form of sheet that was some melted and cold rolled to 30 $\mu$ thickness; resistance measured by Keithly D.C. Amplifier amplifying voltage output of sample due to varying magnetic field; $\rho_{273}/\rho_{15} = 10$ .
44	41	Van Gorp, G.J.	1967	R	5.2		Same as above except annealed at 10 <sup>-6</sup> torr at 1600°C; $\rho_{273}/\rho_{15} = 15$ .
45 <sup>a</sup>	42	Brushlins, J.P., Vladimirovskaya, T.M., and Praktevskikh, A.A.	1966	A	293		0.01-0.05 C, 0.03-0.05 O <sub>2</sub> , 0.000-0.01 H <sub>2</sub> , 0.2-0.22 Si, 0.27-0.65 Fe, 0.03-0.16 Al; 22 mm x 0.42 mm diameter rod forged from ingots at 1173-1323 K; specimen heated in He atmosphere prior to forging; samples annealed at 1273 K for 30 minutes; measurements in vacuum; measurement temperature not reported, however assumed to be 293 K.
46 <sup>a</sup>	42	Brushlins, J.P., et al.	1966	A	293		Same as above except specimen cold-hardened.
47 <sup>a</sup>	42	Brushlins, J.P., et al.	1966	A	293		Same as above except diameter 0.96 mm; annealed specimen.
48 <sup>a</sup>	42	Brushlins, J.P., et al.	1966	A	293		Same as above except specimen cold-hardened.
49 <sup>a</sup>	42	Brushlins, J.P., et al.	1966	A	293		Same as above except diameter 1.33 mm; annealed specimen.
50 <sup>a</sup>	42	Brushlins, J.P., et al.	1966	A	293		Same as above except specimen cold-hardened.
51 <sup>a</sup>	43	Mrs. G. Gebhardt, E., and Bürschkebel, W.	1965	K	273-1762		0.06 O <sub>2</sub> , 0.01 H <sub>2</sub> , 0.04 H <sub>2</sub> ; fused by electron beam; 0.5 mm diameter wire 16 cm long; annealed at 1500°C for 15 minutes at 1.5 x 10 <sup>-6</sup> torr.
44		Mrs. G.	1946				Not shown in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Specimen Designation	Composition (weight percent), Specifications and Remarks
52	45	Taylor, M.A. and Smith, C.H.L.	1962	A	20-273	V(JM)	99.63 V; ingot from Johnson Matthey Co.; specimen cut to about 10 x 1 x 1 mm; degassed in alcohol; electrolytically polished in dilute H <sub>2</sub> SO <sub>4</sub> , rinsed, annealed at 1073 K for 5 hr in vacuum at 10 <sup>-6</sup> mm Hg, cooled and process repeated again; this was done to remove strains; accurate to $\pm 1\%$ ; error due to irregular cross sectional area.
53	45	Taylor, M.A. and Smith, C.H.L.	1962	A	20-273	V(BMI)	99.92 V; specimen from Battelle Memorial Institute; other specifications same as above.
54	45	Taylor, M.A. and Smith, C.H.L.	1962	A	20-273	V1(USNM)	99.85 V; specimen from U.S. Bureau of Mines; other specifications same as above.
55*	45	Taylor, M.A. and Smith, C.H.L.	1962	A	20-273	V2(USNM)	Similar to the above.
56	46	Burger, J. and Taylor, M.A.	1961	A	224-246		99.9 V from Battelle Memorial Institute, Columbus, OH; 0.005 C, 0.001 Si, 0.001 Cr, 0.04 Fe, 0.005 Al, 0.001 Cu, 0.001 Ni, 0.008 W, 0.0020 O; $\rho_{100} = 23 \pm 1 \times 10^{-9} \Omega$ ; data extracted from figure.
57	47	Brown, J.A. and Wayman, C.H.	1960	A	126-282		99.7 V, Cu reduced; annealed at 950°C; degassed at 1500°C; 0.025 in. diameter, 8 cm long; heating cycle; no indication of sudden discontinuity but deviation from linearity at 200 K; data extracted from figure.
58	47	Brown, J.A. and Wayman, C.H.	1960	A	140-288		Same as above except cooling cycle; data extracted from figure.
59	48 49	White, G.K. and Wood, S.R.	1959	A	15-390	V4	99.9 V obtained from Electrometallurgical Co.; specimen diameter 3.55 mm; annealed in vacuum at 1573 K; residual resistivity $\rho_0 = 4.83 \times 10^{-9} \Omega$ m.
60*	50	Semenov, G.V.	1957	V	295		Unspecified sample of V; thermal coefficient of electrical resistivity $+0.28\%/degree$ .
61	51	Urbak, D. and Vert, C.	1955	-	93	V1	Polycrystalline; 0.14 C, 0.12 O, 0.11 Ni; bec structure; foil 0.2 cm wide, 0.008 cm thick, and 4 cm long; IR drop method.
62	51	Urbak, D. and Vert, C.	1955	-	93	V2	Same as above.
63*	52	Potter, H.H.	1941	A	273		Irregular pellets; specimen dimensions of 0.6 mm square and 6 mm in length.
64	53	Geserow, G.J., Zehlechi, J.E., Wang, T.Y., Weinstock, H., and Schmidt, F.A.	1961	C	3.92-298.0		Sample prepared using electrotransport technique; annealing time 800 hr, cross section was reduced to 0.85 mm square from cylinder 1.6 cm long and 2 mm diam; this was done to remedy too low signal to noise ratio; $\rho_{100}/\rho_0 = 1970$ and $\rho_{100}/\rho_{10} = 1770$ , $\rho_0 = 0.01 \times 10^{-9} \Omega$ m; superconducting transition temperature, $T_c = 3.46 \pm 0.02$ K which was suppressed by 0.6T field produced by superconducting solenoid;

\*See above in figure.

TABLE 2. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

Data Set No.	Author(s)	Year	Method Used	Temp. Range, K	Mass and Specimen Designation	Composition (weight percent), Specifications and Remarks
64 53 (cont.)	Guetzen, G.J., et al.	1961	C	3.92-298.0		additionally electron-electron scattering ( $\rho_{ee} = 1.6 \pm 0.2 \times 10^{-11} \Omega \text{ m K}^{-2}$ ), electron-phonon interband scattering ( $\rho_{id} = (2.6 \pm 0.3) \times 10^{-11} \Omega \text{ m K}^{-2}$ ), and electron-phonon intraband scattering $\rho_{ps} = (7.3 \pm 1.1) \times 10^{-10} \Omega \text{ m K}^{-2}$ .
65 54	Tsai, C.L., Fogaly, R.L., Weinstock, R., and Schmidt, F.A.	1961	C	4.5-298.1	Sample I	Sample purified using electrotransport technique; RRR = 1760; $\rho_0 = 0.0109 \times 10^{-10} \Omega \text{ m}$ ; superconducting transition temperature $5.43 \pm 0.03 \text{ K}$ ; data extracted from figure.
66 54	Tsai, C.L., et al.	1961	C	4.6-90.5	Sample II	Similar to above except less pure and $\rho_0 = 0.261 \times 10^{-10} \Omega \text{ m}$ ; superconducting transition temperature $5.77 \text{ K}$ ; data extracted from figure.
67 55	Zylov, B.R. and Groot, H.	1961	K	298.9-745.0		Sample (RRR ~ 400) received from Dr. J. Cook of National Research Council, Canada; density $6.095 \text{ g cm}^{-3}$ .
68 56	L'vov, S.H. and Ruzhnikov, V.P.	1965	A	292-1670		99.98 V iodide vanadium; measurement in vacuum furnace $2 \times 10^{-5}$ to $8 \times 10^{-4} \text{ mm Hg}$ ; data extracted from figure.
69 57	Polatshii, V.E.	1978	-	200-2100		Recommended values for pure V; values based on 1968-IPTS and corrected for thermal expansion; confidence interval of the values varied from $-2.8\%$ near room temperature to $1.6-2.0\%$ in the region 1800-2000 K.

That shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF VANADIUM V  
 [Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \cdot m$ ]

T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$						
<b>DATA SET 1</b>																					
2175	134.9	500	34.4	137.2	12.8	136.8	10.3	76.9	2.3	218	14.87										
2200	135.1	700	44.2	161.8	13.4	141.3	10.8	82.3	2.7	225	15.51										
2300	136.7	900	59.35	168.6	14.1	145.9	11.4	97.4	4.0	228	15.77										
2400	137.3	1100	70.1	170.9	14.7	150.4	11.9	103.3	4.5	239	16.60										
2500	138.4	1300	80.3	177.7	15.2	155.0	12.6	108.7	5.1	242	16.79										
2600	139.6	1500	90.1	184.5	15.9	159.5	13.3	117.3	5.9	246	17.13										
2700	140.8	1700	99.2	182.2	16.2	164.0	13.5	126.5	6.7	254	17.73										
2800	142.1	1900	107.9	191.3	16.6	175.4	14.9	134.5	7.4	257	17.99										
3000	144.8	<b>DATA SET 5</b>																			
3200	147.6	300	24.22	191.4	17.0	180.0	15.5	149.6	6.8	262	18.40										
3400	150.6	500	34.3	200.4	17.7	184.5	16.2	156.1	9.4	266	18.82										
3600	153.9	700	44.2	209.6	18.4	191.4	16.3	174.4	11.0	269	19.01										
3800	157.2	900	50.7	220.9	19.7	193.6	17.4	184.6	11.9	279	20.76										
4000	160.8	1100	61.7	236.9	21.2	202.7	18.11	195.9	13.0	283	20.02										
<b>DATA SET 2</b>																					
1800	101.7	1100	71.5	243.7	21.2	230.0	20.9	213.2	14.4	<b>DATA SET 11</b>											
1950	108.7	1300	80.2	248.2	22.2	239.1	21.6	223.4	15.4	81	2.60										
2100	115.7	1500	88.2	252.8	23.1	252.8	22.5	230.4	15.9	100	4.26										
2190(1)	119.9	1700	96.0	259.6	23.4	252.8	22.8	246.0	17.6	130	6.96										
2190(2)	135.2	1900	103.8	266.7	24.3	261.9	24.0	248.7	17.8	154	9.19										
2400	136.2	2000	107.7	275.6	25.2	268.7	24.7	251.4	18.2	170	10.82										
2550	140.6	<b>DATA SET 6</b>																			
2700	143.2	11.4	0.69	282.4	25.8	277.8	25.5	257.9	18.7	191	12.35										
2850	146.0	25.1	0.69	291.5	26.8	286.9	26.2	260.5	18.9	199	12.91										
3000	149.0	38.9	1.04	300.6	27.7	300.6	27.4	270.2	20.0	215	14.34										
3150	152.3	52.6	1.74	<b>DATA SET 7</b>																	
3300	155.8	57.1	1.98	20.5	0.69	<b>DATA SET 8</b>															
3450	159.5	66.2	2.67	25.1	0.81	95.8	3.9	273.5	20.2	218	14.57										
3600	163.5	73.1	3.37	34.3	0.81	101.2	4.4	277.2	20.6	229	15.39										
3750	167.7	82.2	4.18	45.7	1.40	112.5	5.4	287.5	21.3	247	16.79										
3900	172.2	86.7	4.76	59.4	2.09	116.2	5.8	290.7	21.6	250	17.12										
4050	176.9	95.8	5.45	70.8	2.90	132.4	7.2	296.1	22.0	260	17.82										
4200	181.9	100.4	6.15	75.3	3.60	141.0	8.1	<b>DATA SET 10</b>													
<b>DATA SET 3<sup>a</sup></b>																					
4.2	1.75	107.2	4.85	84.5	4.06	141.0	8.1	78	2.49	<b>DATA SET 12</b>											
293	27.8	114.0	7.66	86.7	4.53	177.1	11.2	84	2.90	5.4	0.012										
<b>DATA SET 4</b>																					
300	23.9	120.8	8.56	84.5	4.53	179.8	11.4	86	3.05	15.4	0.021										
<b>DATA SET 5</b>																					
300	23.9	136.8	9.98	86.7	4.53	188.9	12.2	91	3.54	17.5	0.026										
<b>DATA SET 6</b>																					
300	23.9	139.0	10.7	91.3	5.11	193.8	12.7	113	5.49	19.3	0.032										
<b>DATA SET 7</b>																					
300	23.9	143.6	11.1	98.1	5.80	203.5	13.6	124	6.59	22.0	0.040										
<b>DATA SET 8</b>																					
300	23.9	146.1	11.2	102.7	6.50	229.3	16.1	136	7.60	23.4	0.052										
<b>DATA SET 9</b>																					
300	23.9	152.7	12.2	109.5	7.19	237.4	16.9	157	9.56	26.6	0.076										
<b>DATA SET 10</b>																					
300	23.9	157.9	12.2	118.6	8.00	257.3	19.5	164	10.16	31.2	0.136										
<b>DATA SET 11</b>																					
300	23.9	160.1	11.2	123.1	8.93	263.2	19.4	205	13.78	33.3	0.187										
<b>DATA SET 12</b>																					
300	23.9	162.2	12.2	130.0	9.40	271.9	20.4	208	14.08	40.3	0.284										
<b>DATA SET 13</b>																					
300	23.9	176.2	12.2	132.2	9.63	288.5	21.8	215	14.72												

<sup>a</sup>Not shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ		
<b>DATA SET 12 (cont.)</b>															
44.4	0.432	5.9	0.228	5.8	0.022	90.3	2.57	69.40	1.72	20.2	0.0541	20.2	0.0541		
55.6	0.796	6.2	0.228	6.7	0.024	99.9	4.22	77.30	2.31	22.9	0.0844	22.9	0.0844		
76.5	2.16	7.0	0.228	8.0	0.024	112.2	5.39	300	19.6	27.2	0.143	27.2	0.143		
81.6	2.53	7.5	0.228	9.3	0.024	130.4	6.97	<b>DATA SET 18</b>						31.4	0.223
87.0	3.06	8.1	0.250	10.9	0.028	150.4	8.83	6	0.861	35.7	0.340	35.7	0.340		
92.8	3.48	8.5	0.230	36.2	0.236	161.9	9.89	7	0.879	38.6	0.438	38.6	0.438		
96.9	3.84	9.2	0.230	39.2	0.309	176.4	11.1	10	0.873	45.6	0.708	45.6	0.708		
105	4.51	10.0	0.232	43.1	0.431	184.2	11.8	10	0.879	54.1	1.13	54.1	1.13		
112	5.29	10.9	0.234	48.7	0.596	197.9	12.9	13	0.879	59.8	1.48	59.8	1.48		
120	6.02	11.9	0.236	54.7	0.853	215.4	14.3	13	0.879	65.4	1.90	65.4	1.90		
136	6.85	12.9	0.239	50.4	1.07	229.5	15.5	14	0.879	69.7	2.18	69.7	2.18		
145	8.05	14.1	0.247	77.7	2.39	247.3	16.8	17	0.845	73.9	2.39	73.9	2.39		
155	8.86	15.8	0.250	82.1	2.61	260.3	17.9	20	0.902	75.3	2.74	75.3	2.74		
<b>DATA SET 13</b>															
5.6	0.51	19.1	0.259	90.3	3.38	261.8	18.0	22	0.914	82.4	3.23	82.4	3.23		
6.6	0.51	20.9	0.269	100.7	4.30	274.8	19.0	25	0.932	86.6	3.65	86.6	3.65		
7.3	0.52	22.8	0.280	113.3	5.50	<b>DATA SET 17</b>						92.3	4.14		
8.1	0.52	24.9	0.296	130.8	7.08	5.49	0.0133	28	0.967	95.1	4.56	95.1	4.56		
9.2	0.52	27.9	0.322	154.5	9.27	5.95	0.0136	30	0.991	100.7	5.06	100.7	5.06		
10	0.52	30.4	0.354	170.9	10.7	7.21	0.0140	32	1.020	106.4	5.48	106.4	5.48		
11	0.52	33.8	0.407	191.3	12.5	10.10	0.0162	35	1.068	113.4	6.11	113.4	6.11		
13	0.52	36.2	0.460	217.6	14.6	13.08	0.0200	37	1.115	117.7	6.53	117.7	6.53		
14	0.53	39.4	0.533	250.7	17.1	15.99	0.0255	38	1.162	120.5	6.95	120.5	6.95		
15	0.53	48.3	0.778	283.4	19.7	18.56	0.0363	39	1.186	129.0	7.58	129.0	7.58		
16	0.53	54.3	1.06	<b>DATA SET 15</b>						42	1.245	133.2	8.07	133.2	8.07
17	0.54	61.7	1.51	5.4	0.009	22.00	0.0473	43	1.293	144.5	8.63	144.5	8.63		
18	0.54	73.2	2.24	5.8	0.009	24.34	0.0605	45	1.346	150.1	9.61	150.1	9.61		
22	0.57	79.9	2.72	6.3	0.013	26.03	0.0734	46	1.388	158.6	10.2	158.6	10.2		
49	1.14	86.2	3.27	7.9	0.013	28.38	0.0933	47	1.441	165.7	10.9	165.7	10.9		
54	1.33	88.1	3.38	7.9	0.013	29.99	0.112	<b>DATA SET 19</b>						174.1	11.8
57	1.51	93.3	3.82	8.0	0.013	31.34	0.131	5.5	0.00959	181.2	12.4	181.2	12.4		
62	1.80	107.0	5.03	9.3	0.013	33.35	0.154	5.5	0.00589	185.4	12.8	185.4	12.8		
66	2.10	111.1	5.36	11.2	0.017	35.98	0.198	5.5	0.00589	192.5	13.5	192.5	13.5		
83	3.38	126.7	7.84	12.1	0.018	37.00	0.226	5.5	0.00589	198.1	13.7	198.1	13.7		
109	5.72	139.3	7.99	13.4	0.020	38.01	0.244	5.7	0.0163	206.6	14.8	206.6	14.8		
125	7.18	166.8	10.2	15.2	0.022	39.23	0.272	6.1	0.0163	215.1	15.3	215.1	15.3		
148	9.27	177.5	11.2	16.2	0.026	40.09	0.294	6.5	0.0168	227.8	16.2	227.8	16.2		
182	12.1	186.8	12.9	17.9	0.029	41.92	0.346	7.2	0.0168	233.4	16.8	233.4	16.8		
242	17.1	196.3	12.8	20.1	0.039	42.88	0.370	7.9	0.0174	240.5	17.3	240.5	17.3		
245	17.2	203.5	13.3	22.9	0.055	44.00	0.400	9.1	0.0182	246.1	17.9	246.1	17.9		
255	17.2	213.9	14.2	23.8	0.077	44.90	0.431	10.7	0.0193	256.0	18.7	256.0	18.7		
273	19.5	231.4	15.6	29.7	0.119	46.12	0.471	11.9	0.0206	270.2	19.6	270.2	19.6		
<b>DATA SET 20</b>															
5.5	0.226	265.9	18.2	35.9	0.225	46.92	0.503	12.9	0.0223	<b>DATA SET 20</b>					
				39.2	0.296	47.58	0.529	13.8	0.0239	5.65	0.083	5.65	0.083		
				42.7	0.417	60.15	1.33	14.7	0.0255	5.67	0.088	5.67	0.088		
				62.1	1.33	64.20	1.40	15.8	0.0311	5.68	0.091	5.68	0.091		
				66.6	1.62	67.40	1.58	17.9	0.0412						

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ
<b>DATA SET 28 (cont.)</b>											
6.72	0.091	220.9	15.7	49.5	2.10	659	46.9	485.6	30.6	1177	74.0
7.76	0.093	223.8	16.0	54.7	2.53	789	54.5	591.8	33.9	1218	75.6
8.94	0.093	234.1	16.6	62.9	3.38	875	60.5	614.6	33.9	1275	78.1
9.69	0.093	239.9	17.2	69.2	4.02	975	65.4	720.9	38.3	1317	80.1
10.7	0.094	244.3	17.5	76.4	4.87	1032	69.2	796.8	40.5	1455	87.1
11.8	0.096	251.6	18.0	96.0	7.00	<b>DATA SET 28P</b>					
12.4	0.096	254.5	18.4	105.4	8.50	933.4	44.9	880.4	43.8	1507	89.2
13.6	0.098	272.0	19.6	115.7	9.78	1047.4	49.2	1047.4	49.2	1546	90.8
14.8	0.10	<b>DATA SET 21*</b>									
15.8	0.10	300	23	125.0	10.8	1000	68.0	1130.9	52.5	<b>DATA SET 33</b>	
16.7	0.10	300	23	140.5	12.8	1100	71.4	1206.8	54.7	1591	92.3
17.8	0.10	300	23	157.0	14.9	1200	78.5	1267.8	56.9	1626	94.5
18.8	0.11	<b>DATA SET 22</b>									
19.9	0.11	293	21.72	172.5	16.6	1300	83.5	1381.2	61.3	1690	97.1
20.6	0.13	293	21.72	183.9	18.3	1400	88.2	<b>DATA SET 32</b>			
21.0	0.13	1500	87.66	195.3	19.6	1500	92.8	283	20.9	293	241
22.5	0.20	1550	89.01	208.7	21.3	1700	101.5	301	22.5	<b>DATA SET 34</b>	
28.4	0.27	1600	91.93	228.4	23.6	1800	105.6	320	23.5	293	75.5
34.3	0.44	1650	94.03	251.1	26.0	<b>DATA SET 29</b>					
43.1	0.81	1700	95.83	257.3	26.8	1000	68.0	337	25.0	<b>DATA SET 35</b>	
48.9	1.1	1750	97.06	267.7	27.9	1100	73.4	359	26.4	293	241
57.8	1.3	1800	99.87	<b>DATA SET 25*</b>							
60.7	1.6	1850	101.69	77	2.283	1200	78.5	402	28.9	<b>DATA SET 36</b>	
73.9	2.5	1900	103.56	293.2	19.62	1300	83.5	442	31.7	11	3.1
86.9	3.7	1950	105.40	<b>DATA SET 26</b>							
98.6	4.7	2000	107.28	373	21.6	1400	88.2	485	33.5	77	5.9
101.5	5.1	2050	109.01	573	40.2	1500	92.8	482	34.4	273	22.0
116.1	6.4	2100	110.70	773	52.1	1600	97.5	500	35.8	293	23.8
121.9	6.8	<b>DATA SET 23*</b>									
124.8	7.2	300	22.6	973	62.8	1700	101.5	520	36.9	410	31.4
130.7	7.6	300	22.6	1173	72.6	1800	105.6	541	38.4	468	35.1
136.5	8.2	<b>DATA SET 24</b>									
140.8	8.7	5.2	1.07	1373	81.8	1900	109.5	590	41.3	575	41.4
146.6	9.2	7.2	1.28	1573	90.8	<b>DATA SET 30</b>					
152.5	9.8	10.3	1.28	1773	99.8	293	21.02	617	43.2	680	46.6
159.7	10.3	13.5	1.28	1973	99.8	373	27.0	631	45.1	773	53.5
165.6	10.9	17.6	1.27	5.2	0.92	573	40.2	684	46.9	779	52.2
178.7	11.9	21.7	1.27	65	2.44	773	52.1	730	50.2	875	57.7
183.1	12.4	24.8	1.27	129	8.47	973	62.8	796	53.9	925	61.4
187.4	13.0	28.9	1.26	229	17.16	1173	72.6	822	55.3	979	62.1
194.2	13.5	34.1	1.69	259	25.4	1373	81.8	849	56.9	1090	68.7
203.4	14.3	39.2	1.68	337	25.4	1573	90.8	907	59.9	<b>DATA SET 37</b>	
212.2	14.9	44.4	1.89	400	30.0	1773	99.8	932	61.1	6.5	0.81
218.0	15.4	530	39.0	459	26.2	1973	99.8	962	62.7	22	0.85
				530	39.0	<b>DATA SET 31</b>					
						341.2	25.1	999	64.6	56	1.89
						417.2	28.4	1051	67.6	59	2.05
								1087	69.5	115.6	6.85

\*Not shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (cont. lued)

T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ
<b>DATA SET 37 (cont.)</b>													
134.4	0.56	77	4.9	184	15.3	293	28.0	20	1.56	220	22.0	<b>DATA SET 57 (cont.)</b>	
169.8	11.72	89	6.1	187	15.0	<b>DATA SET 49*</b>		77	3.98	232	22.9		
191.0	13.55	100	7.1	190	16.0	<b>DATA SET 49*</b>		273	20.34	242	23.6		
198.3	14.21	108	8.1	195	16.4	293	24.6	<b>DATA SET 55*</b>		253	24.5		
213.5	15.48	116	8.7	198	16.6	<b>DATA SET 50*</b>		20	1.34	261	25.0		
233.6	17.16	133	9.5	201	16.0	293	28.6	77	3.96	282	26.7		
242.6	17.89	136	9.8	204	17.2	<b>DATA SET 51*</b>		273	20.39	<b>DATA SET 58</b>			
260.8	19.33	134	10.7	207	17.4	273	20.5	224	18.4	140	15.1		
278.0	20.88	141	11.6	210	17.8	283	22.0	225	18.5	148	15.9		
291.0	21.69	144	11.8	214	18.2	1187	73.7	226	18.7	156	16.7		
313.6	24.90	151	12.5	216	18.2	1302	80.0	228	18.8	165	17.3		
349.6	26.13	155	12.8	222	18.8	1378	80.0	229	19.0	170	17.8		
<b>DATA SET 38</b>													
5	0.82	160	13.3	223	19.0	1437	85.6	230	19.1	178	18.5		
20	0.82	163	13.7	225	19.1	1437	86.2	232	19.2	187	19.3		
40	1.3	166	14.1	227	19.4	1446	88.7	233	19.4	190	19.4		
60	2.1	171	14.4	231	19.6	1537	91.2	236	19.7	197	20.0		
80	3.4	175	14.8	234	19.9	1542	90.6	237	19.8	207	20.9		
121	7.4	179	15.2	236	20.3	1584	93.2	238	19.9	224	22.3		
161	11.2	183	15.5	243	21.1	1632	95.4	239	20.0	227	22.5		
201	14.5	186	15.9	249	21.5	1643	95.2	241	20.1	232	22.5		
241	17.8	192	16.5	253	21.8	1683	97.1	242	20.2	238	23.2		
280	20.9	199	17.2	258	22.2	1724	98.8	243	20.3	247	24.1		
300	22.5	206	17.8	261	22.6	1752	101.0	244	20.5	256	24.8		
320	23.8	212	18.4	266	23.0	1762	100.8	245	20.5	267	25.5		
338	25.3	219	20.4	277	24.1	<b>DATA SET 32</b>		246	20.6	273	25.9		
<b>DATA SET 39</b>													
4.2	3.9	244	21.3	<b>DATA SET 43</b>		5.07	2.6	<b>DATA SET 57</b>		288	27.1		
<b>DATA SET 40</b>													
4.2	4.4	249	21.7	<b>DATA SET 44</b>		5.15	1.7	<b>DATA SET 57</b>		15	4.84		
<b>DATA SET 41</b>													
16	1.9	256	22.3	<b>DATA SET 45</b>		5.15	1.7	<b>DATA SET 57</b>		20	4.87		
21	2.1	262	22.9	<b>DATA SET 46*</b>		5.15	1.7	<b>DATA SET 57</b>		30	4.97		
26	2.1	263	23.2	<b>DATA SET 46*</b>		77	6.48	<b>DATA SET 57</b>		40	5.21		
38	2.4	275	24.0	<b>DATA SET 46*</b>		273	22.67	<b>DATA SET 57</b>		50	5.57		
47	2.7	287	25.0	<b>DATA SET 47*</b>		<b>DATA SET 32</b>		<b>DATA SET 57</b>		75	7.13		
56	3.2	299	26.0	293	23.6	<b>DATA SET 32</b>		<b>DATA SET 57</b>		100	9.08		
68	4.1	<b>DATA SET 42</b>		<b>DATA SET 47*</b>		<b>DATA SET 32</b>		<b>DATA SET 57</b>		150	13.5		
<b>DATA SET 42</b>													
131	10.1	20	0.74	126	13.8	<b>DATA SET 32</b>		<b>DATA SET 57</b>		200	17.5		
144	11.7	77	3.18	132	14.5	<b>DATA SET 32</b>		<b>DATA SET 57</b>		250	21.5		
155	12.7	273	19.54	139	14.9	<b>DATA SET 32</b>		<b>DATA SET 57</b>		273	23.1		
161	13.3	<b>DATA SET 47*</b>		145	15.6	<b>DATA SET 32</b>		<b>DATA SET 57</b>		295	24.7		
168	13.9	293	23.8	151	16.2	<b>DATA SET 32</b>		<b>DATA SET 57</b>		390	31.4		
173	14.3	<b>DATA SET 47*</b>		167	17.5	<b>DATA SET 32</b>		<b>DATA SET 57</b>					
178	14.9	<b>DATA SET 47*</b>		174	18.2	<b>DATA SET 32</b>		<b>DATA SET 57</b>					
<b>DATA SET 43</b>													
<b>DATA SET 44</b>													
<b>DATA SET 45</b>													
<b>DATA SET 46*</b>													
<b>DATA SET 47*</b>													

\*not shown in figure.

TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$	T	$\rho$				
<u>DATA SET 60*</u>		283 26.0		0.0114		0.0195		8.97		0.0135		44.13		0.395		83.60		2.75		<u>DATA SET 66 (cont.)</u>		83.60		2.75	
<u>DATA SET 61</u>		6.318		0.0114		13.494		8.96		0.0147		53.89		0.147		90.52		3.22							
<u>DATA SET 62</u>		6.756		0.0116		13.678		9.72		0.0147		57.22		0.936											
93 17.96		6.842		0.0117		14.395		9.91		0.0159		81.93		2.49											
<u>DATA SET 63*</u>		6.963		0.0117		14.550		10.73		0.0158		85.28		2.92											
93 16.49		7.066		0.0118		14.874		11.17		0.0178		204.4		11.2											
<u>DATA SET 65 (cont.)</u>		7.140		0.0119		15.033		11.62		0.0171		264.5		15.4											
273 18.2		7.185		0.0118		15.188		12.58		0.0185		298.1		19.1											
<u>DATA SET 64 (cont.)</u>		7.203		0.0118		15.207		12.58		0.0197															
<u>DATA SET 64</u>		7.229		0.0119		15.702		13.62		0.0197															
3.923		7.502		0.0121		16.273		14.17		0.0213															
4.145		7.607		0.0122		16.350		14.45		0.0230															
4.175		7.723		0.0122		16.406		14.46		0.0249															
4.216		7.925		0.0122		16.606		14.46		0.0273															
4.270		7.946		0.0124		16.664		15.34		0.0239															
4.289		7.994		0.0124		17.032		15.65		0.0254															
4.316		8.208		0.0125		17.155		16.94		0.0285															
4.377		8.331		0.0127		17.309		16.95		0.0309															
4.449		8.433		0.0129		17.509		17.63		0.0328															
4.473		8.628		0.0139		18.128		19.09		0.0315															
4.516		8.776		0.0131		18.647		19.86		0.0347															
4.598		8.849		0.0130		18.541		20.67		0.0406															
4.673		9.261		0.0135		18.577		21.51		0.0440															
4.793		9.441		0.0136		19.782		22.38		0.0466															
4.849		9.728		0.0137		20.133		22.83		0.0494															
4.898		9.793		0.0137		20.320		23.77		0.0567															
4.993		10.066		0.0144		20.024		23.77		0.0602															
5.004		10.156		0.0144		20.950		23.77		0.0614															
5.185		10.338		0.0146		21.012		25.73		0.0664															
5.282		10.336		0.0147		21.310		25.74		0.0718															
5.294		10.371		0.0146		21.624		26.25		0.0746															
5.347		10.571		0.0150		21.967		27.32		0.0823															
5.414		10.792		0.0153		22.448		27.87		0.0891															
5.467		10.828		0.0153		22.853		28.44		0.0982															
5.618		10.863		0.0153		23.079		28.44		0.102															
5.705		11.295		0.0160		23.079		30.20		0.119															
5.802		11.585		0.0164		23.079		31.43		0.134															
6.199		11.833		0.0167		23.079		32.70		0.139															
6.268		11.885		0.0170		23.36		33.36		0.160															
6.275		12.085		0.0170		23.42		34.72		0.173															
6.456		12.216		0.0172		23.68		35.42		0.187															
		12.448		0.0176		23.87		36.87		0.215															
		12.725		0.0181		24.15		37.61		0.237															
		12.903		0.0184		24.20		38.15		0.267															
		12.957		0.0185		24.72		40.74		0.306															
		13.160		0.0189		24.83		41.57		0.338															
		13.416		0.0194		24.83		42.41		0.365															

\*Not shown in figure.



TABLE 3. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF VANADIUM V (continued)

T	P
DATA SET 69 (cont.) <sup>a</sup>	
1100	67.84
1200	72.76
1300	77.52
1400	82.16
1500	86.70
1600	91.17
1700	95.59
1800	99.99
1900	104.84
2000	108.84
2100	113.35

<sup>a</sup>Not shown in figure.

### 3.2. Zirconium

There are 43 data sets available from 23 references [33,49,123-144] for the electrical resistivity of zirconium specimens with purity 99.8-99.99%. The temperature range covered by these data sets is from 1.7 to 2127 K. The information on specimen characterization and measurement condition for each of the data sets is given in table 5. The data sets are tabulated in table 6 and shown partially in figure 4.

From liquid-helium temperature to room temperature the only set of data for high-purity zirconium is that of White and Woods [49] (data set 27) on a specimen with RRR = 168. Above 100 K these data appear to be trustworthy, but their reliability below 100 K is not sufficient to permit reliable interpretation in terms of any low-temperature conduction mechanism. However, White and Woods pointed out a  $T^{4.5}$  dependence of the temperature-dependent resistivity above 13 K as indicating rather strong electron-phonon s-s interband scattering. This and earlier work of Kemp et al. [141] (data set 31) on a specimen with RRR = 25 was supported fifteen years later by Volkenshtein et al. [131] (data set 12) using a specimen with RRR = 34. Furthermore, the data of Volkenshtein et al. [131] suggested the existence of a  $T^2$  term below 13 K which was undoubtedly related to electron-electron scattering.  $T^3$  dependence indicative of s-d electron-phonon scattering was neither explored nor reported by these or other low-temperature studies [131-137,140]. Careful low-temperature studies on a very pure specimen is required to detect such dependence.

The recommended values below 293 K are based on the data of White and Woods [49] (data set 27), who studied the purest specimen ( $\rho_0 = 0.25 \times 10^{-8} \Omega \text{ m}$ ).

In the temperature range up to  $T_{\alpha-\beta} = 1137 \text{ K}$  there appears to be fairly good agreement ( $\pm 10\%$ ) among the data of Bykov et al. [127] (data set 7), L'vov et al. [33] (data set 13), Peletskii et al. [133] (data set 15), Powell and Tye [138] (data sets 22-24), Bing et al. [143] (data set 37), and of Cook et al. [144] (data set 38). The recommended values up to 800 K are based on the data of Peletskii et al. [133] (data set 15). In the temperature range from 800 to 1137 K the recommendations were guided by the data of Cezairliyan and Righini [123,124] (data set 2), Peletskii et al. [133] (data set 15) and those of Kiselev [139] (data sets 25,26). Data of Cezairliyan and Righini [123-125]

(data sets 2-5) and those of Peletskii et al. [133] (data sets 15,16) were used to generate the recommended values for  $\beta$ -Zr between 1137 to 2127 K. The value of  $141.3 \times 10^{-8} \Omega \text{ m}$  for liquid Zr at 212 K follows the only available data of Martynyuk and Tsapkov [129] (data set 10).

The recommended values of the electrical resistivity given in table 4 and shown in figures 5 and 6 are for zirconium of 99.95% purity or higher, but those below 100 K are applicable specifically to samples with  $\rho_0 = 0.250 \times 10^{-8} \Omega \text{ m}$ . The table gives both values uncorrected and corrected for thermal expansion, while figures 5 and 6 show only the uncorrected values along with experimental data which were used to generate these values. Thermal expansion values needed to carry out thermal expansion correction were taken from ref. [190]. The uncertainty in the recommended values is estimated to be within  $\pm 2\%$  below 1137 K,  $\pm 3\%$  up to the melting point, and  $\pm 4\%$  for the liquid value at 2127 K.

Zirconium is a transition element, and its low-temperature electrical resistivity depends upon the type as well as on the concentration of impurities. The low-temperature electrical resistivity of low purity zirconium is rather difficult to estimate. Data so far available does not permit one to establish the upper limit of  $\rho_0$  for which Matthiessen's rule can be applied to estimate electrical resistivity.

The data available in the literature for the temperature dependence of a bulk sample is reviewed in this report. However, additional information on the electrical resistivity is available in refs. [50,52,82,90,145-183]. Attention is directed to refs. [163,179,184-186] for data on irradiated samples, refs. [106,111,187,188] for data on films, ref. [188] for data on doped zirconium and ref. [189] for data on pressure dependence of resistivity.

TABLE 4. RECOMMENDED VALUES FOR THE ELECTRICAL RESISTIVITY OF ZIRCONIUM<sup>a</sup>[Temperature, T, K; Electrical Resistivity,  $\rho$ ,  $10^{-8} \Omega \text{ m}$ ]

T	$\rho$		T	$\rho$	
	uncorrected	corrected		uncorrected	corrected
1	0.250	0.250	700	104.2	104.5
4	0.250	0.250	800	114.9	115.3
7	0.250	0.250	900	123.1	123.6
10	0.253	0.253	1000	128.8	129.4
15	0.283	0.283	1100	132.0	132.8
20	0.357	0.357	1137	132.6(a)	133.4(a)
25	0.491	0.490	1137	110.8( $\beta$ )	111.3( $\beta$ )
30	0.712	0.711	1150	111.1	111.7
40	1.443	1.441	1200	112.2	112.8
50	2.495	2.492	1300	114.5	115.2
60	3.75	3.75	1400	116.5	117.3
70	5.15	5.14	1500	118.6	119.6
80	6.64	6.63	1600	120.4	121.5
90	8.18	8.17	1700	122.3	123.5
100	9.79	9.78	1800	124.0	125.4
150	17.85	17.84	1900	125.8	127.4
200	26.35	26.33	2000	127.5	129.3
250	34.9	34.9	2100	129.1	131.0
273	38.8	38.8	2127	129.5(s)	131.4(s)
293	42.1	42.1	2127		141.3(l)
300	43.3	43.3			
350	51.9	51.9			
400	60.3	60.3			
500	76.5	76.6			
600	91.5	91.7			

<sup>a</sup>The values are for polycrystalline zirconium of purity 99.95% or higher, but those below 200 K are applicable specifically to zirconium having a residual resistivity of  $0.250 \times 10^{-8} \Omega \text{ m}$ . The columns headed uncorrected and corrected refer to values uncorrected and corrected for thermal expansion, respectively. Solid line separating tabular values indicates solid to liquid state transformation, while dotted line indicates solid phase transition.

a: cph;  $\beta$ : bcc.

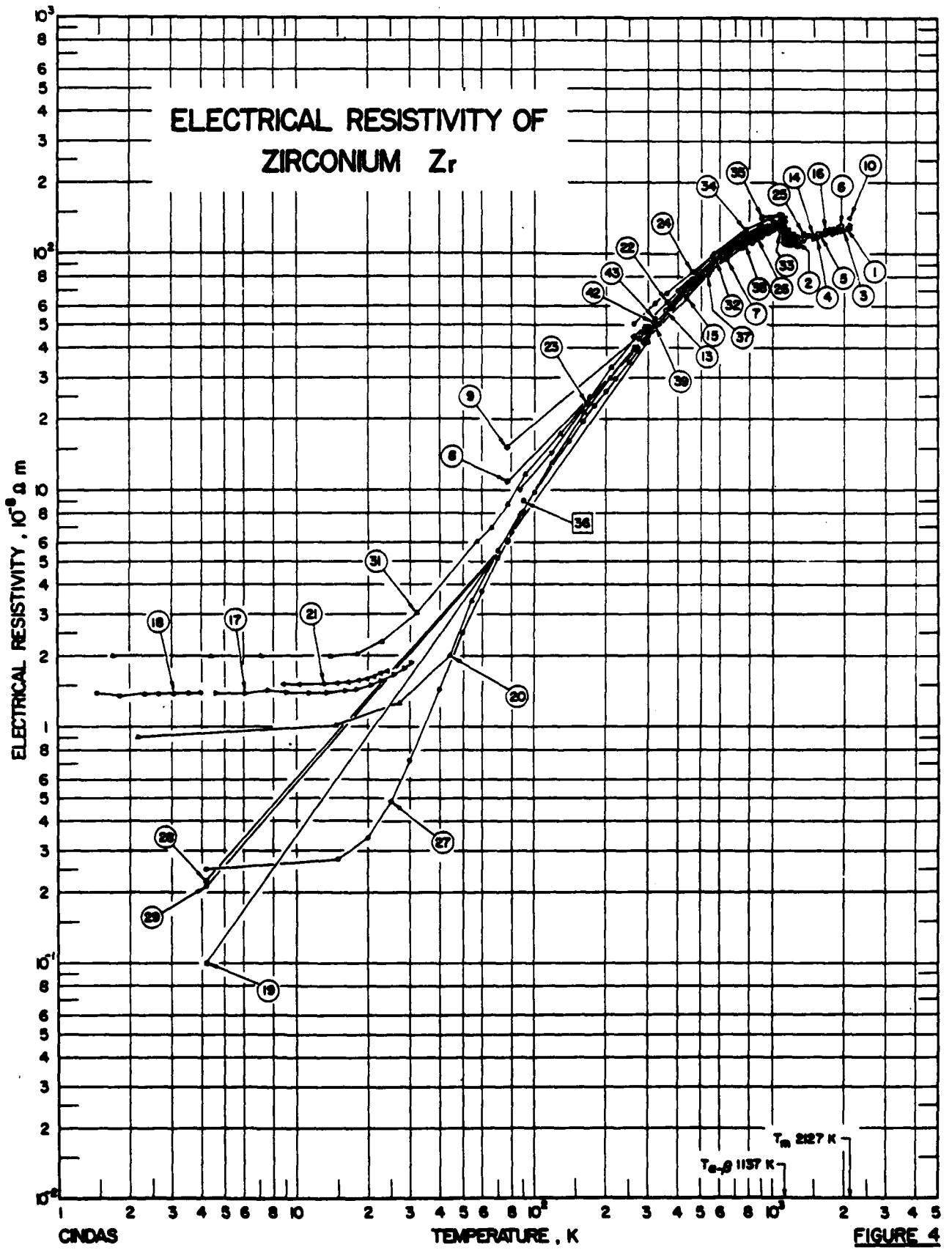
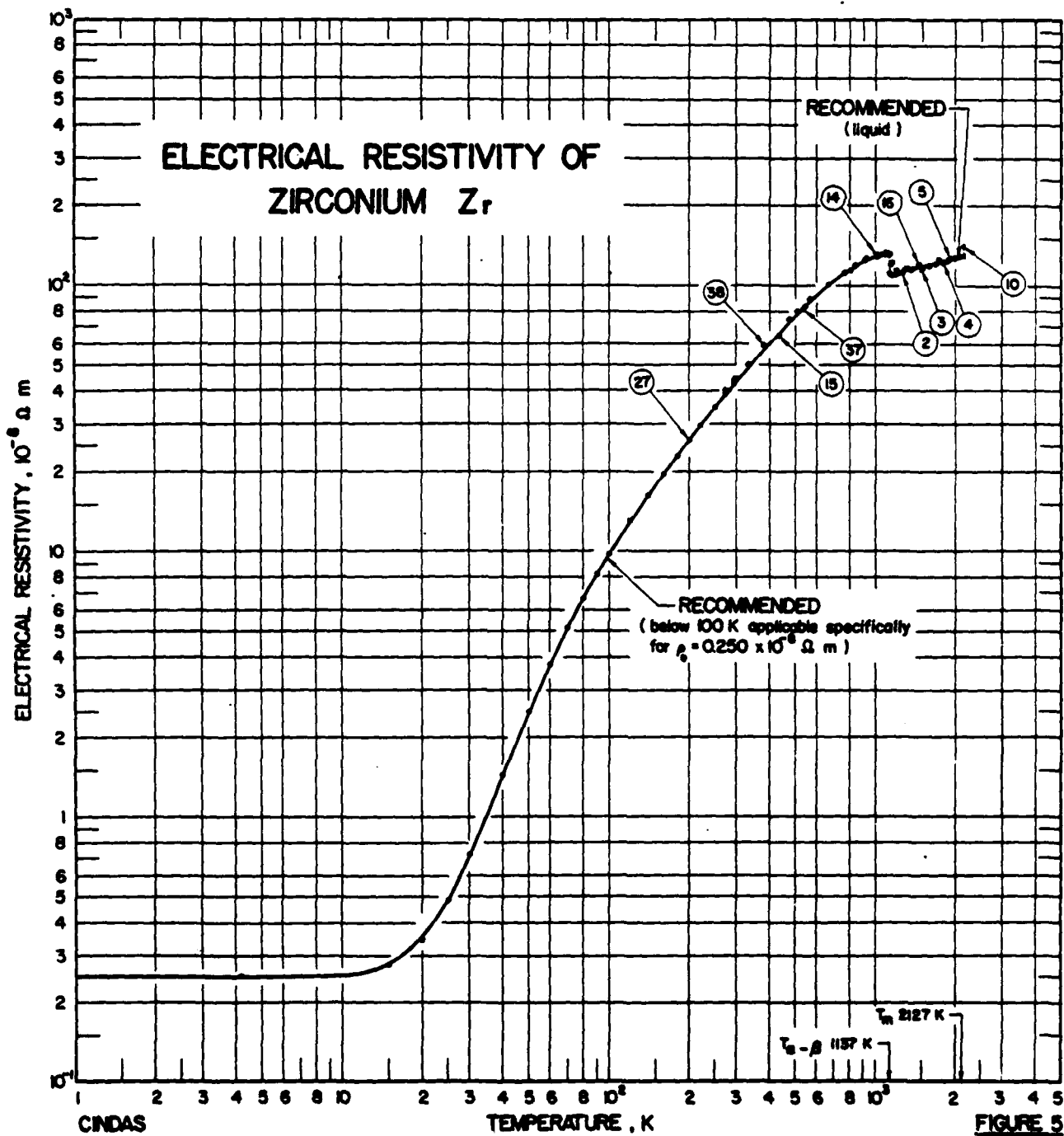


FIGURE 4



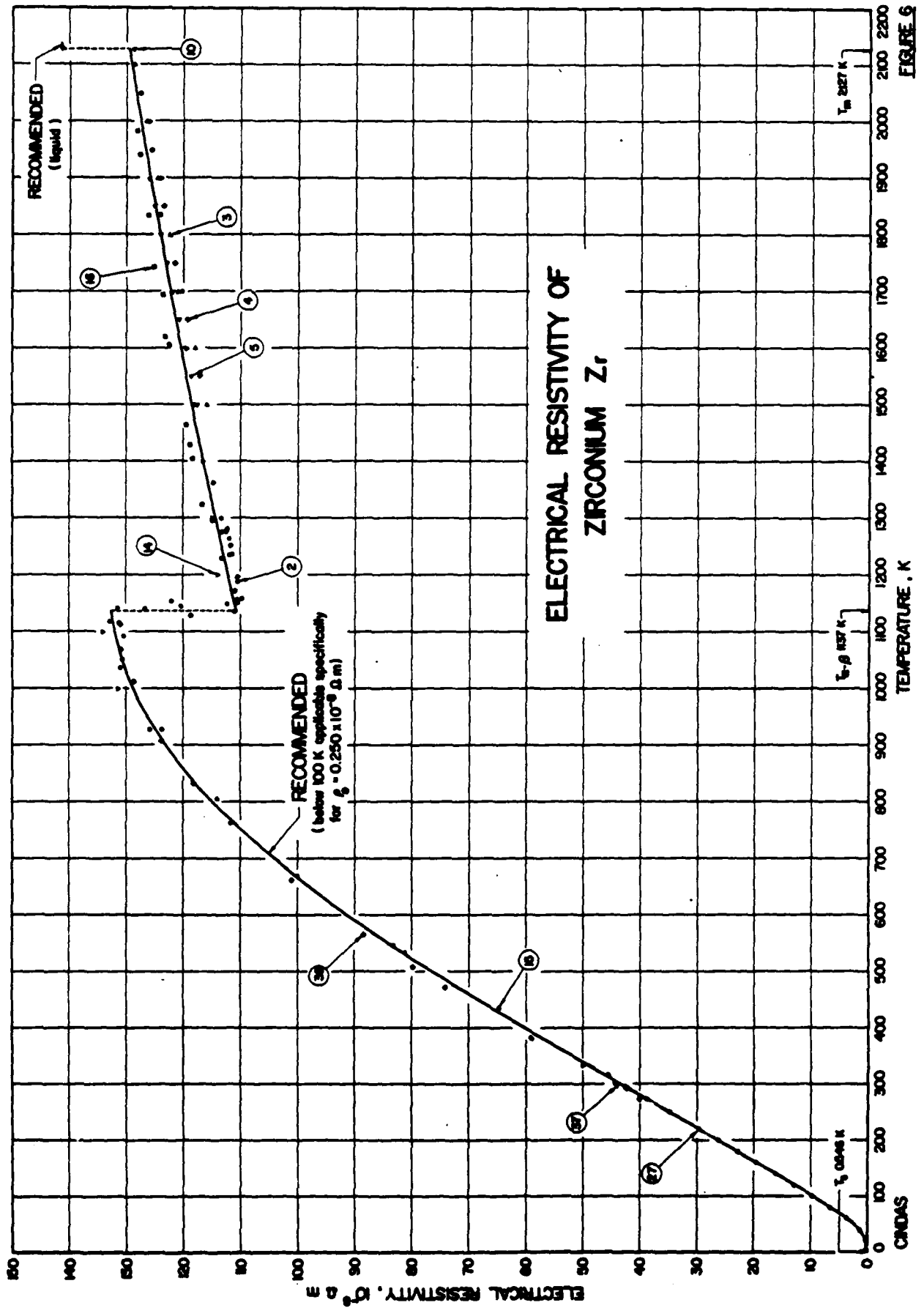


FIGURE 6

TABLE 5. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ZIRCONIUM Zr

Ref. Set No.	Author(s)	Year	Method Used	Temp. Range, K	Mass and Specimen Designation	Composition (weight percent), Specifications and Remarks
1 123	Cesariyev, A. and Righini, P.	1974	T	2097-2128	Specimen 11	99.98 Zr, 125 ppm O, 40 ppm Hf, 30 ppm Fe, 6 ppm Cr, 3.3 ppm Ni, 3 ppm Al, 2.1 ppm W, 1.5 ppm Mn, 1.5 ppm Si, 1.0 ppm Ti, less than 6 ppm other elements; specimen 76.2 mm long, 6.3 mm O.D., 0.25 mm thickness; small rectangular hole (0.5 x 1 mm) fabricated in the wall at middle of the specimen; approximated blackbody conditions; $T_0 = 2128$ K; data extracted from figure; estimated inaccuracy in the measurement is 13% (imprecision 10.05%).
2 123, 124	Cesariyev, A. and Righini, P.	1974	T	1092-1265	Specimen 3	99.98 Zr, 125 ppm O, 40 ppm Hf, 30 ppm Fe, 6 ppm Cr, 3.3 ppm Ni, 3 ppm Al, 2.1 ppm W, 1.5 ppm Mn, 1.5 ppm Si, and 1.0 ppm Ti; specimen tube fabricated from rods by removing center portion using an electro-erosion technique; nominal dimensions of specimen were 76.2 mm long, 6.3 mm O.D., and wall thickness 0.5 mm; outer surfaces of the specimen were polished to reduce heat loss due to thermal radiation; $\alpha$ - $\beta$ transformation temperature 1147 $\pm$ 10 K; data extracted from figure; estimated inaccuracy of the measurement is 12%.
3 125	Cesariyev, A. and Righini, P.	1974	T	1500-2100	Specimen 1	99.98 Zr, polycrystalline from Materials Research Corp., 6 ppm Cr, 3.3 ppm Ni, 125 ppm O, 2.1 ppm W, 3.0 ppm Al, 30 ppm Fe, 40 ppm Hf, 1.5 ppm Mn, 1.5 ppm Si, 1.0 ppm Ti; nominal dimensions are 76.2 mm length, 25.4 mm (effective length), 6.3 mm O.D., 0.5 mm wall thickness, and 0.5 x 1 mm rectangular blackbody hole; inaccuracy in measured value is 12%.
4 125	Cesariyev, A. and Righini, P.	1974	T	1500-2100	Specimen 2	Similar to the above except different specimen.
5 125	Cesariyev, A. and Righini, P.	1974	T	1500-1900	Specimen 3	Similar to the above except different specimen.
6 126	Mira, G., Hummel, H., and Kambeck, H.	1974	B	1173-1973	$\beta$ -Zr	Drawn Zr wire of 0.5 mm diameter of Margrade (produced by electron beam zone melting) from Materials Research Corp., Orangeburg, NY; <10 ppm O, 40 ppm Cr, 15 ppm Al, 50 ppm Fe, 100 ppm Hf, and <75 ppm other; surface impurities were removed by polishing mechanically and electrolytically; wire was heated by D.C. for 30 minutes at 1650 C in high vacuum of $5 \times 10^{-6}$ torr for recrystallization; data extracted from figure.
7 127	Dyckov, V.F., Rudnev, I.I., and Solov'ev, V.A.	1972	A	288-1282	Iodide Zirconium	0.056 Fe, <0.001 V, 0.0065 Mo, 0.0074 Nb, 0.012 Cu, 0.0041 Cr, 0.0041 Ni; measurements in $10^{-4}$ mm Hg vacuum; data extracted from figure.
8 128	Dyckov, V.F., Libshansk, Yu. B., and Mal'tsev, V.A.	1973	A	77,295	$\alpha$ -Zr	99.8 Zr (iodide); remelted in arc furnace.
9 128	Dyckov, V.F., et al.	1973	A	77,295	$\omega$ -Zr	Similar to above except subjected to hydrostatic pressure of 100 kbars at room temperature to get metastable $\omega$ -Zr phase.



TABLE 5. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ZIRCONIUM Zr (continued)

Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Mass and Specimen Designation	Composition (weight percent), Specifications and Remarks
12	Marynyuk, M.M. and Tsyplov, V.I.	1973	Z	2127		99.76 Zr; values are reported for solid and for liquid at melting point; accuracy of measurements $\pm 5\%$ .
11c	Beale, G.	1973		4.2-293		Polycrystalline zirconium 100-250 Å thick vacuum deposited films onto very smooth, optically polished, square-shaped alkaline borosilicate substrates at room temp.; prior to the film condensation, the substrates had been degassed by baking in vacuum at 350°C for 6 hr and cleaned afterwards by both ultrasonic agitation at 50 kHz and ionic bombardment using a glow discharge of 5 kV; zirconium was evaporated from a copper liquid-nitrogen-cooled crucible employing a 270° beam deflection electron gun under pressure of the order of $10^{-4}$ torr; both the film thickness and the condensation rate were accurately controlled with a piezoelectric quartz crystal monitor maintained at the substrate temperature; the films were annealed for 3 hr at 300°C to remove frozen-in structural defects and subsequently cooled down to 4.2 K (tetragonal crystal structure characteristic of the $\beta$ phase as shown by electron-diffraction analysis) using liquid helium as the refrigerant; the specimens were always kept under vacuum at the condensation pressure; to minimize the deformation arising from differential thermal expansion between metal and glass, both heating and cooling rates were lower than 1°C/sec; after the annealing process, measurements were taken; to avoid oxidation or adsorption of some other gases, all the experiments were performed in the vacuum conditions utilized for film preparation.
12a	Velibekzain, B.V., Zverev, V.A., and Startsev, V.E.	1971	A	0.6-71.0		99.9 Zr, polycrystal; tabulated values calculated from $\rho_T/\rho_{173}$ values reported graphically assuming $36.8 \cdot 10^{-10}$ m for $D_{173}$ ; $D_{100}/D_{173} = 34$ .
13	L'vov, S.H., Mal'ko, P.I., and Munchenko, V.P.	1971		309-1331		99.9 Zr; sample was prepared from bars (rods) obtained by iodide process; $D_{100}/D_{173} = 26$ ; data extracted from figure.
14	Zherov, G.A.	1970		1000-2000	NETU 95-67-66	99.56 Zr, 0.23 Nb, 0.02 Fe, 0.04 Hf, 0.005 Co, 0.01 Hg, 0.03 Ti, 0.005 Ni, 0.005 Al, 0.01 Sn, iodide zirconium; density $6.59 \text{ g cm}^{-3}$ ; rod specimen 56.6 mm length and 9.84 mm diameter; measurements in $5 \times 10^{-3}$ mm Hg; greatest relative error in determination 2.8%; average values of several heating and cooling experiments.
15	Polozakii, V.E., Brushkin, V.P., and Sobol, Ya.G.	1970	A	302-1363		99.9 Zr, 0.01 Co, 0.005 Ni, 0.01 O <sub>2</sub> , 0.009 Fe, 0.03 Nb, 0.002 Al, 0.005 Cu, 0.003 Ti, 0.005 Si; compact samples obtained by electron-beam sintering in vacuum; specimen dimensions are cylinder 60 mm long and 9 mm diameter; sample heated in resistance furnace with a molybdenum heater; measurements in $10^{-3}$ mm Hg; experimental error $\pm 1.5$ to 2%.
16	Polozakii, V.E., et al.	1970	A	1229-1983		Same as above except sample heated by electron bombardment.

Not shown in figure.

TABLE 5. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ZINCBIUM Zr (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Name and Specimen Designation	Composition (weight percent), Specifications and Remarks
17	134	Elliott, R.O. and Hill, H.H.	1970		4.6-30.6		105 ppm O <sub>2</sub> , 8 ppm H <sub>2</sub> , 33 ppm C, and 27 ppm Fe; heating cycle; data extracted from figure.
18	134	Elliott, R.O. and Hill, H.H.	1970		1.5-4.0		Same as above except cooling cycle; data extracted from figure.
19	135	Becterton, J.O. and Raston, D.S.	1968		4.2-300		No details given.
20	136	Cloward, F.W., Jr. and Kempter, G.D.	1968	A	2.1-295		Commercial specimen 95-175 ppm O <sub>2</sub> , 40 ppm H <sub>2</sub> , <40 ppm N <sub>2</sub> , <1000 ppm HF, <1000 ppm Nb, 200 ppm Fe, 100 ppm Al, <100 ppm each Ti, V, Zr, Mo, and Pb; $\rho_0 = 0.8 \times 10^{-6} \Omega \cdot m$ ; annealed condition; cylindrical specimen 0.25 in. diameter and 1 in. long; data extracted from figure; average of heating and cooling.
21	137	Cape, J.A. and Hahn, R.H.	1965		8.8-24.1		Specimen cut from a button arc-cast in an inert atmosphere; finished sample was then measured as machined without annealing; specimen was $1 \times 0.1 \times 0.01$ in.; estimated absolute values of the resistivities are accurate to approximately $\pm 2\%$ ; values calculated from graphically reported values of $\rho_T/\rho_{300}$ and tabulated values of $1.522 \times 10^{-6} \Omega \cdot m$ for $\rho_{300}$ .
22	138	Fusilli, R.H. and Tye, R.P.	1961	A	264-1196	No. 715	Graphite-melted Zr, 0.018 Fe, 0.043 C, 0.007 Al, 0.007 Nb, 0.0075 H <sub>2</sub> , 0.1-0.6 O <sub>2</sub> ; extruded; average of heating and cooling; data extracted from figure.
23	138	Fusilli, R.H. and Tye, R.P.	1961	A	87-1230	Van Arkel Zr	Van Arkel zirconium, 0.012 Fe, 0.016 C, 0.0025 H <sub>2</sub> , and 0.3-0.6 O <sub>2</sub> ; cold swaged; average of heating and cooling; data extracted from figure.
24	138	Fusilli, R.H. and Tye, R.P.	1961	A	264-886	No. 050	Arc melted low-carbon Zr; 0.045 Fe, 0.01 C, 0.008 H <sub>2</sub> , 0.11 O <sub>2</sub> ; extruded; average of heating and cooling; data extracted from figure.
25	139	Kiselev, H.A.	1961		730-1353		Specimen prepared from iodide metal; average of heating thermocouple and optical pyrometer measurements; $T_{\alpha-\beta} = 1138$ K; data extracted from figure.
26	139	Kiselev, H.A.	1961		855-1356		Same as above; average values of cooling thermocouple and optical pyrometer measurements; data extracted from figure.
27	49	White, G.E. and Woods, S.B.	1959	A	4.2-295	Zr3	99.95 Zr, 132 ppm Hf, 79 ppm C, 24 ppm Fe, 11 ppm Ni, 21-50 ppm O <sub>2</sub> , 3-50 ppm H <sub>2</sub> , <100 ppm Zn, 2-7 ppm each Ca, Cr, Mo, Si, H <sub>2</sub> , and <10 ppm other elements; arc cast annealed 4 hr at 1100°C, swaged at room temp.; annealed for 15 min. at 1000°C and finally for 15 min. at 800°C in a vacuum $1-2 \times 10^{-6}$ mm Hg; values calculated from tabulated values of ideal resistivity ( $\rho_1$ ), $\rho_{295} = 42.4 \times 10^{-6} \Omega \cdot m$ and $\rho_0/\rho_{295} = 5.96 \times 10^{-3}$ .
28	140	Berlincourt, T.G.	1958		4.2-298	Zr1	Crystal bar from Westinghouse, 0.001 Ca, 0.016 Cu, 0.075 Fe, 0.002 H, 0.001 N, 0.016 O <sub>2</sub> , 0.013 Si; $\rho_{295}/\rho_{300} = 170$ .

TABLE 5. MEASUREMENT INFORMATION ON THE ELECTRICAL RESISTIVITY OF ZIRCONIUM Zr (continued)

Data Set No.	Ref. No.	Author(s)	Year	Method Used	Temp. Range, K	Specimen Designation	Composition (weight percent), Specifications and Remarks
29	140	Berlincovert, T.G.	1958		4.2-300	Zr2	Same as above except $\rho_{1773}/\rho_{300} = 179$ .
30*	140	Berlincovert, T.G.	1958		4.2-300	Zr2'	Same as above except $\rho_{1773}/\rho_{300} = 176$ .
31	141	Kemp, W.R.G., Klamann, P.G., and White, G.K.	1956	A	1.7-293	JM5000	99.99 Zr from Messrs. Johnson, Matthey and Co., Ltd.; 3 mm diam. rod; annealed for 5 hr. at 950°C in vacuo; data extracted from figure; $\rho_0 = 1.96 \times 10^{-10} \Omega \cdot m$ .
32	142	Adenstedt, H.K.	1952	B	276-1213	Zr660	99.9 Zr, 0.1 Hf, 0.02 Fe, <0.005 Ti, <0.005 Al, <0.005 Si, hafnium free from Foote Mineral Co.; samples prepared from as-deposited iodide crystal bars; cold-swaged condition; Rockwell hardness A-36; first heating run; values obtained by multiplying $43.2 \times 10^{-10} \Omega \cdot m$ (resistivity at 0°C) by resistivity ratio as function of temperature reported graphically.
33	142	Adenstedt, H.K.	1952	B	924-1299	Zr660	Same as above except second heating run.
34	142	Adenstedt, H.K.	1952	B	404-1189	Zr681	Similar to the above except as deposited iodide crystal bar, 0.036 Hf, <0.005 Fe, <0.005 Ti, <0.005 Al, <0.005 Si; Rockwell hardness A-22; first heating run.
35	142	Adenstedt, H.K.	1952	B	902-1127	Zr681	Same as above except first cooling run.
36	142	Adenstedt, H.K.	1952	B	90	Zr757	Similar to the above except 0.032 Hf, 0.044 O <sub>2</sub> , 0.005 Ni, 0.005 Si, and <0.003 each Al, Fe, and Ti; cold-swaged, machined and annealed at 973 K from iodide crystal bar; 0.22 in. diam. and 10 in. length; $\rho_0 = 39.6 \times 10^{-10} \Omega \cdot m$ .
37	143	King, G., Fink, F.W., and Thompson, H.B.	1951		273-533	Hastingshouse ingot D-216	Pure Zr, 0.04 Hf, 0.04 Fe, 0.02 Ni, 0.007 Ti, 0.003 Sn, 0.001 Al; arc-melted ingot of WM crystal bar produced from lot CB-37; ingot forged at 1650 to a 1 in. square bar; measurements made at Mettelle.
38	144	Cook, L.A., Coetlemans, L.B., and Johnson, W.R.	1950	B	277-1277	Low-Hf	Foote crystal bar, 0.04 Hf, 0.06 Si, 0.04 Fe, 0.004 Al, 0.005 each Cu, Ca, 0.001 each Ti, Mn, Pb, Mo, 0.01 Mg, 0.003 each Ni, Cr; machined to smooth cylinder 0.358 in. diam.; annealed above recrystallization temp.; data extracted from figure.
39	144	Cook, G.L., et al.	1950	B	303-323	Sample A	Same as above except machined to 0.306 in. diam. cylinder.
40*	144	Cook, G.L., et al.	1950	B	302-315	Sample B	Same as above except swaged from 0.306 in. diam. to 0.125 in. diam. (84% reduction in area).
41*	144	Cook, G.L., et al.	1950	B	302-322	Sample C	Same as sample B except annealed for 1 hr. at 500°C.
42	144	Cook, G.L., et al.	1950	B	303-320	Sample D	Same as sample C except swaged from 0.125 in. diam. to 0.048 in. diam. (83% reduction in area).
43	144	Cook, G.L., et al.	1950	B	301-321	Sample E	Same as sample D except annealed for 1 hr. at 500°C.

\*Not shown in figure.



TABLE 6. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF ZIRCONIUM Zr (continued)

T	ρ	T	ρ	T	ρ	T	ρ	T	ρ	T	ρ
<b>DATA SET 15 (cont.)</b>											
928.1	126.0	1.5	1.39	19.9	1.60	957	130	1138	114.6	220	29.651
1037	131.1	1.8	1.36	21.3	1.64	1009	133	1159	114.8	250	34.851
1081	136.7	2.3	1.36	22.7	1.68	1106	136	1175	115.2	273	39.851
1118	132.9	2.6	1.39	24.1	1.73	1145	142	1197	117.2	295	42.651
1154	122.2	3.0	1.36	<b>DATA SET 22</b>		1159	139	1218	117.9	<b>DATA SET 28</b>	
1152	110.5	3.5	1.39	264	44.7	1179	126	1318	118.7	4.2	0.224
1236	112.0	3.9	1.39	364	62.2	1190	120	1334	119.8	77	6.11
1282	112.4	4.0	1.40	461	78.0	1205	121	1340	120.1	298.6	42.6
1300	113.5	<b>DATA SET 19</b>		524	86.3	1213	122	1353	122.0	<b>DATA SET 29</b>	
1343	114.9	4.2	0.1	564	92.1	1230	121	<b>DATA SET 26</b>		4.2	0.213
<b>DATA SET 16</b>											
1229	113.4	300	42.3	621	99.2	<b>DATA SET 24</b>		855	117.2	<b>DATA SET 30*</b>	
1275	113.4	<b>DATA SET 20</b>		664	104	264	90.2	971	127.0	4.2	6.08
1296	116.9	2.1	0.91	709	109	324	60.8	1043	133.1	77	42.6
1324	116.7	14.7	1.62	764	115	364	67.7	1086	133.5	<b>DATA SET 31</b>	
1405	116.5	27.3	1.2	812	119	421	76.9	1102	132.9	1.7	2.00
1430	118.9	44.1	2.0	863	123	461	83.5	1122	129.9	4.4	2.00
1465	119.6	54.7	3.4	912	128	521	91.2	1138	118.9	7.1	2.00
1606	122.6	70.6	5.5	1006	134	564	97.2	1147	118.4	14	2.00
1630	123.3	87.5	7.9	1111	136	615	103	1156	117.6	18	2.05
1694	123.7	105	10.8	1131	136	664	109	1172	117.2	23	3.30
1743	123.2	118	13.1	1139	131	712	114	1234	117.2	32	3.04
1835	126.2	132	15.5	1142	127	769	119	1278	117.4	57	6.10
1855	126.3	149	18.6	1148	121	861	123	1312	117.4	66	6.97
1941	127.8	163	21.4	1150	116	866	128	1331	118.1	77	8.72
1983	128.2	180	24.7	1153	116	<b>DATA SET 25</b>		1340	119.6	91	11.7
<b>DATA SET 17</b>											
4.6	1.39	190	26.5	1162	115	738	111.3	<b>DATA SET 27</b>		129	17.4
4.9	1.40	208	29.9	1176	115	770	113.9	4.2	0.251	172	24.8
6.1	1.39	246	35.2	1196	116	867	121.7	15	0.276	212	33.1
7.6	1.43	261	37.2	<b>DATA SET 23</b>		927	126.1	20	0.341	292	47.1
9.1	1.40	271	39.3	87	10.0	949	127.4	25	0.486	293	48.9
10.4	1.40	278	40.3	118	14.3	971	128.7	30	0.721	<b>DATA SET 32</b>	
11.4	1.39	285	41.2	167	23.2	1002	130.4	40	1.451	276	43.6
13.6	1.40	295	43.2	267	40.1	1031	131.1	50	2.501	461	76.2
16.2	1.42	<b>DATA SET 21</b>		367	57.6	1049	131.8	60	3.751	580	94.0
18.0	1.45	8.8	1.52	464	73.7	1068	131.8	70	5.151	689	108
20.7	1.50	10.2	1.52	564	90.1	1099	132.2	80	6.451	841	130
23.8	1.57	13.0	1.52	618	99.8	1102	132.2	90	8.151	915	
25.9	1.67	14.0	1.52	644	105	1115	132.2	100	9.801		
28.6	1.77	14.9	1.53	712	111	1121	129.9	120	13.051		
30.6	1.88	15.8	1.53	764	116	1132	126.4	140	16.251		
Not shown in figure.											
16.6	1.54	16.6	1.54	815	120	1132	118.7	160	19.551		
18.3	1.57	18.3	1.57	863	123	1131	116.0	180	22.851		
		909	127	1131	115.2			200	26.351		

TABLE 6. EXPERIMENTAL DATA ON THE ELECTRICAL RESISTIVITY OF ZIRCONIUM 2r (continued)

T	P	T	P	T	P
<u>DATA SET 32 (cont.)</u>		<u>DATA SET 37</u>		<u>DATA SET 41*</u>	
1019	136	273	40.2	302.9	46.7
1137	117	298	44.1	306.2	47.3
1184	117	533	81.3	311.4	48.2
1213	118			317.0	49.4
		<u>DATA SET 38</u>		322.4	50.4
<u>DATA SET 33</u>		277	39.9	<u>DATA SET 42</u>	
924	130	293	42.4	303.1	47.8
1028	133	334	50.1	305.4	48.1
1073	130	382	59.1	309.8	49.0
1085	126	471	74.2	315.3	50.1
1096	124	508	79.9	319.7	50.8
1110	120	543	88.5	320.8	51.0
1122	117	642	101.1	<u>DATA SET 43</u>	
1152	115	763	111.7	301.1	49.0
1176	115	832	118.2	303.2	49.4
1253	114	908	123.9	305.3	49.8
1299	116	1013	128.7	310.4	50.6
		1069	131.1	315.6	51.6
		1113	131.1	321.6	52.8
		1129	118.8	<u>DATA SET 39</u>	
<u>DATA SET 34</u>		1136	111.1	303.5	45.9
404	69.2	1156	110.6	304.4	46.2
570	99.8	1172	111.0	306.0	46.5
779	127	1197	111.6	307.4	46.6
931	139	1253	112.6	308.0	46.6
993	142	1277		309.3	47.1
1026	144			310.8	47.2
1050	144	<u>DATA SET 39</u>		313.8	47.8
1078	145	303.5	45.9	323.0	49.6
1107	145	304.4	46.2	<u>DATA SET 40*</u>	
1127	131	306.0	46.5	302.1	46.5
1142	122	307.4	46.6	305.0	47.0
1159	121	308.0	46.6	309.9	48.0
1189	122	309.3	47.1	315.9	49.2
		310.8	47.2		
<u>DATA SET 35</u>		313.8	47.8		
982	141	323.0	49.6		
1008	145				
1096	138	<u>DATA SET 40*</u>			
1114	126	302.1	46.5		
1127	124	305.0	47.0		
		309.9	48.0		
<u>DATA SET 36</u>		315.9	49.2		
90	9.03				

\*Not shown in figure.

#### 4. ACKNOWLEDGMENTS

This work was supported by the Office of Standard Reference Data (OSRD) of the National Bureau of Standards (NBS), U.S. Department of Commerce. The extensive documentary activity essential to this work was supported by the Defense Logistics Agency (DLA) of the U.S. Department of Defense.

The authors wish to express their appreciation and gratitude to Dr. H. J. White, Jr. of the NBS Office of Standard Reference Data for his guidance, cooperation, and sympathetic understanding during the course of this work.

## 5. APPENDICES

### 5.1. Methods for the Measurement of Electrical Resistivity

At the Center for Information and Numerical Data Analysis and Synthesis (CINDAS) of Purdue University, the experimental methods for the measurement of electrical resistivity have been classified into various categories according to a similar scheme used by CINDAS for the classification of methods for the measurement of thermal conductivity [191, pp. 13a-25a]. This classification scheme of CINDAS is presented below. Note that the letters in parentheses following the respective methods are the code letter used in the 'Method Used' column of the Table of Measurement Information for indicating the experimental methods used by the various authors.

#### Methods for the Measurement of Electrical Resistivity

##### A. Steady-State Methods

1. Voltmeter and ammeter direct reading method (V) [192, p. 159; 193, pp. 244-5]
2. Direct-current potentiometer method (A) [194, pp. 151-8]
  - a. 4-probe potentiometer method
3. Direct-current bridge methods (B) [194, pp. 144-51]
  - a. Kelvin double bridge method
  - b. Mueller bridge method
  - c. Wheatstone bridge method
4. Direct-heating method (K) [195,196]

##### B. Non-Steady-State Methods

1. Periodic current method
  - a. Direct connection to sample
    - (1) Alternating-current potentiometer method (C) [194, pp. 161-2]
  - b. No connection to sample
    - (1) Rotating magnetic field method (R) [197]
2. Non-periodic current method
  - a. Direct connection to sample
    - (1) Transient (subsecond) method (T) [198]



### 5.2. Conversion Factors for the Units of Electrical Resistivity

The recommended values and experimental data for the electrical resistivity tabulated in this work are in the units:  $10^{-8} \Omega \text{ m}$ . Conversion factors for the units of electrical resistivity, which may be used to convert the values given in ( $10^{-8} \Omega \text{ m}$ ) to values in other units, are given below.

#### Conversion Factors for the Units of Electrical Resistivity

Units to be Converted to	Multiply the Value Given in ( $10^{-8} \Omega \text{ m}$ ) by
ohm-meter ( $\Omega \text{ m}$ )	$1 \times 10^{-8}$
ohm-centimeter ( $\Omega \text{ cm}$ )	$1 \times 10^{-6}$
ohm-inch ( $\Omega \text{ in.}$ )	$3.937 \times 10^{-7}$
ohm-foot ( $\Omega \text{ ft}$ )	$3.281 \times 10^{-8}$
microhm-centimeter ( $\mu\Omega \text{ cm}$ )	1
abohm-centimeter ( $\text{ab}\Omega \text{ cm}$ )	$1 \times 10^3$
statohm-centimeter ( $\text{stat}\Omega \text{ cm}$ )	$1.113 \times 10^{-18}$
emu (= $\text{ab}\Omega \text{ cm}$ )	$1 \times 10^3$
esu (= $\text{stat}\Omega \text{ cm}$ )	$1.113 \times 10^{-18}$
ohm-circular mil per foot ( $\Omega \text{ cmil ft}^{-1}$ )	6.015

Example:  $1.000 \times 10^{-8} \Omega \text{ m} = 3.937 \times 10^{-7} \Omega \text{ in.}$

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